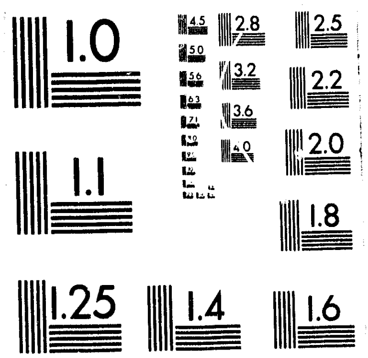
3.5 Gasification Ash and Slag Characterization

Final Report IS NOT Included
(Project was extended to June 30, 1993)


1.0
1.1
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6.3

3.6 Coal Science

COAL SCIENCE
EARTH RESOURCE EVALUATION AND MANAGEMENT

Final Technical Progress Report
for the Period July 1, 1989, to December 31, 1992

by

Joseph H. Hartman, Project Manager

Energy and Environmental Research Center
University of North Dakota
Box 8213, University Station
Grand Forks, North Dakota 58202

Task Contracting Officer's Representative: Leroy Dockter

for

United States Department of Energy
Laramie Project Office
2020 Grand Avenue
Suite 450
P.O. Box 1189
Laramie, Wyoming 82070

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EARTH RESOURCE EVALUATION AND MANAGEMENT

1.0 INTRODUCTION

The general "Coal Science" objective of the Energy and Environmental Research Center (EERC) North Dakota Mining and Mineral Resources Research Institute (NDMMRRI) was directed towards a fuller utilization of energy and associated energy-related data, available as published and unpublished documents, to better evaluate resource potential through a thorough knowledge and understanding of the geologic context of the resource. This objective was implemented through computer-based data management systems involving specific field examples. Much of the coal data for the nonmarine Upper Cretaceous and Paleocene of the Western Interior of North America is locked into a historic format that inhibits reinterpretation. Resource calculations are thus necessarily made on data that have typically 1) never been reevaluated, 2) been based on land surveys prior to the U.S. Geological Survey (USGS) 7.5-minute series mapping program, 3) been based on coal bed correlations that lack regional synthesis, 4) been based on coal bed correlations that lack temporal control, 5) been based on coal bed correlations that have not integrated surface and subsurface observations, and 6) been based on geologic observations that predate more rigorous approaches to stratigraphic nomenclature and field practices.

The initial development of the Coal Science project was based on previous knowledge as to the generalization and underutilization of a considerable amount of coal data in far-western North Dakota of the Williston Basin. Earlier work (Hartman, 1984) clearly indicated that the only expedient means of evaluating the numerous available geologic observations was to establish various systems that would allow for a wide variety of geologic observations to be easily cataloged, upgraded, and maintained. The Coal Science program was begun with these objectives.

Within the last three years, the central focus or theme of the Coal Science project has remained consistent. The focus was o develop and implement a (nonmarine) coal-oriented database management system that would permit (and document) the reevaluation and incorporation of a wide variety of data types (and qualities) to produce a uniform means of upgrading our understanding of the stratigraphic context of coal observations. A paramount objective of this system was that access to databases, their subsequent modifications, and the input and output of data be under the control of the primary user. The key word exemplifying the design of the computer system would be flexibility. In addition, the development of the databases would be based on a variety of test-case examples specifically chosen for their utility and variation. With this approach, databases would be revised or modified numerous times to meet specific project demands. Eventually, with the stabilization of the database design and field structure, database enhancements were added, such as improved relational database management features, that provided the user with considerably more computing power in the analysis and display of information.

In summary, the various databases of the Coal Science project, developed for the management of diverse coal-related stratigraphic and geochronologic information, have evolved from relatively simple useful designs to a system or complex of relatively sophisticated databases that are still fundamentally simple to operate, fulfilling the goal of maintaining user compatibility. Because of the basic software programming and the database design, established databases continue to grow and be utilized for a wide range of energy data management tasks.

2.0 GOALS AND OBJECTIVES

A summary of the tasks undertaken through the course of the Coal Science project represents a number of basic objectives. These include A) review of available database systems; B) acquisition of hardware; C) database design of the primary databases (e.g., *MNOS, *UNIT, *LOC, and *SPP [see Section 3.3, Task C]); D) database input and augmentation; E) drilling project, used to assess and characterize database management of subsurface data through a specific case study; F) database design assessment and modification; G) geochemical database studies; H) data presentation, including various form designs, reports, export to graphic programming, and map display; and I) database implementation. Each of these lettered tasks was accomplished as part of an evolving process towards refining the capability of documenting and assessing the geologic context of coal bed data. There has not been, to my knowledge, a comparable approach to the reevaluation of historic coal stratigraphy within the context of modern geologic terminology and current field studies.

3.0 ACCOMPLISHMENTS

The following section will briefly detail the results of the various tasks as listed above. This approach will show the continuity of the development of database management systems with the incorporation of old and new data to produce a synthesized product fully capable of resolving current resource assessment problems. As different tasks were assigned for each project year, the following task letters (e.g., "A") do not conform to previous usage. As enumerated here, these tasks represent a composite or synthesis of the goals and objectives of the Coal Science project.

3.1 Task A—Review of Database Systems

Previous experience suggested that currently available "off-the-shelf" data management and related programs were sufficiently robust to form the basis of the development of a Coal Science data management system. The following factors were considered in this decision: 1) the rapid and likely continued development of sophisticated commercial database management programs, 2) the substantial cost of in-house development of computer programming, and 3) the difficulty of assessing the NDMMRRI's overall long-term computer programming needs. Thus various programs were acquired and tested to determine the best data management system for use at the NDMMRRI. The general data management philosophy was to grow into a system, rather than force an approach because of programming limitations. The basic requirements of the system were that the 1) program designs be easily modifiable, and 2) data once entered be transferrable to other programs as new applications arise.

The initial approach taken in database design and programming was to utilize a combination of a flat or semirelational data manager with a fully relational data managing system. This approach provided a powerful, yet easily modifiable, programming foundation, compatible with the then-current NDMMRRI user needs. The programs chosen for this purpose were Q&A® by Symantec and PARADOX® by Borland. Both programs are powerful, but differ in their approach to data management applications. Q&A® is essentially a flat file manager with semirelational capabilities. PARADOX® is a fully relational data management system with its own programming language.

Q&A® has served as the main program for inputting, manipulating, and reporting lignite, stratigraphic, and paleontologic data. Q&A® differs from many programs (considered both a weakness and strength depending on the application) in its use of the "form" (versus table design) as the basis for data retrieval. The main strengths of Q&A® are its 1) ease of data manipulation (within and between forms or as reported in tables), 2) available screen-length fields, 3) use of internal and multiple external (semirelational) lookup tables, 4) simple but powerful programming procedures, 5) full-feature use of macros, 6) special function keys for data entry replication, and 7) integration of file data with word processing and form merge capabilities. In regards to this later feature, Q&A® contains a word processor, known as the Write Module, that can be employed to utilize information from databases within Q&A®'s File Module. Thus text and data can be merged in any number of formats without redesigning files. Enhancement features (e.g., bold, italics, font scale) available to word processors can be added to data to clarify and augment data presentation. Bitstream fontware was acquired to permit the construction of Prestige fonts of any size and style (e.g., bold, italic, etc.) to allow for greater display power.

The cleverness of the overall design of Q&A® permitted the effective use of its most advanced functions without delay. Relational and programmable programs, such as PARADOX®, which are also simple to use at their basic level, become relatively complicated to achieve comparable Q&A® results. For interactive daily use, where application needs change frequently, a computing system that is easily modified is required. Q&A® works well as a flexible on-line system for data inputting, updating, and retrieval. PARADOX®, which is ultimately more powerful, represents application-oriented programming, which at this point in NDMMRRI data management considerations, is less important than flexibility. Compared to major-market database systems, such as dBASE®, rBASE®, and PARADOX®, Q&A® provides the on-line user with the opportunity to control the data environment without elaborate ritual or protocol. In addition, the cost of Q&A®, through the University of North Dakota, is inexpensive, and has now been acquired by a number of NDMMRRI users interested in expanding their database applications. PARADOX® was initially used with Q&A® for certain data filing maintenance applications. PARADOX® and Q&A® data files were exchanged using a common dBASE or ASCII interface. With the subsequent release of version 4.0 of Q&A®, there has been no need for the continued use of PARADOX® within the developed Coal Science data management system. New Q&A® program features include 1) extended relational data management capabilities; 2) extended programming language; 3) increased (effectively unlimited) field length, with the capability of designing forms with portions of lengthy entries "hidden"; and 4) the ability to select data from pop-up windows for ease of database entry. Important secondary features include 1) word processing capabilities in the File module (e.g., within a given field), 2) spell checking in the File module; 3) the ability to change field names ("Set Field Names") for the purposes of programming and designing new forms in the Write module; 4) expanded macro program facilities, including creation of custom menus to manage access to directories and data; 5) new export and import capabilities with other database managers; 6) greater font control in the various modules; 7) a new compression backup utility; and 8) the ability to check for duplicate forms. Substantial use of these features has been made in the current design and implementation of NDMMRRI Coal Science databases.

3.2 Task B—Acquisition of Hardware

The decision was made early on that purchased computers would have to provide the most computing power for the available dollar. At the time the Coal Science project was undertaken, computing power, rated as machine clock speed, available RAM, caching systems, and available hard disk memory, was improving as the price was coming down. In effect, personal computers purchased through discount houses were never more powerful and, for the power, never cheaper. Through the course of the Coal Science project, computing power has continued to increase, and price has continued to drop. The major decision was to decide on the manufacturer. Gateway 2000 was chosen for the Coal Science project because, at the time, the prices of its computers were the least expensive, and the company's reputation was comparable to other discount mail-order houses. The more expensive computers, such as those manufactured by IBM, were as much as three to four times more expensive to achieve computing parity. In addition, there was no guarantee that the IBM machines would be more durable. An important earlier question was whether or not programming manufactured to run on IBM machines would properly run on IBM clones. To a large extent, these compatibility problems were becoming a thing of the past and were not found to be a problem using Gateway machines.

Through the course of the first year of the project, a computing system was established that used old and newly acquired components. The main data management computer was a Gateway 2000 386-25 mHz machine, with a math coprocessor, 150-MB hard drive, and memory and disk caching. A previously acquired EERC NDMMRRI computer was used for data input by NDMMRRI staff. This machine was a Standard 286, with a math coprocessor and 40-MB hard drive. The computers of the Coal Science data management system were cabled together for the transfer of files (not representing a true network). Data from either computer were outputted to either a Epson LQ-1050 wide carriage line printer or to a Hewlett-Packard Laser Jet II. Bitstream fontware was acquired to extend the flexibility of the output format to data management programs. The data and programming on the main data management computer was archived using an Everex external cassette tape backup system. Input devices include a previously acquired large format GTCO 2436L digitizing board and a video capture system by Jandel and Imaging Technology. Communication devices included a hardware link to the mainframe computing system at the University of North Dakota and a previously acquired MultiTech 1200-baud modem.

The above computing system has remained fully functional throughout the course of the project. Important changes to the system have been upgrades to various component parts to improve performance. These changes basically kept pace with changes in technology and advances in software capabilities, which almost required faster machines with bigger hard drives. The current operating system employs a Gateway 486-33 mHz machine with a 650-MB hard drive and caching capabilities as the main Coal Science data management computer. The 386-25 mHz machine is used in software program development and data input, as well as in generating reports and other documents. In addition, a Gateway 386sx and a Standard 286 computer serve as data inputting devices, most frequently staffed by students. Upgrades to the computers include another 150-MB hard drive for the 386 machine and another 40-MB hard drive for the 286 machine. In addition to the large-format GTGO pad, used primarily for digitizing large maps, a small-format Summagraphics SummaSketch™ II digitizing tablet was installed to function with various types of software used to construct charts and maps (see Task A). In addition, the Hewlett-Packard Laser Jet II was replaced with a Laser Jet III to improve graphic capabilities and provide for significantly greater font control.

To explore the capabilities of image analysis, which represents an important developing technology, a video system was acquired to capture and analyze a variety of image types that would otherwise have to be manually digitized or be treated qualitatively. The video system hardware runs on the main data management computer utilizing a PCVISIONplus™ framegrabber from Imaging Technology. This video image is derived from a Cohu CCD camera, lens (12.5- to 73-mm zoom), and TOYO diopters and is displayed on a high-resolution SONY Trinitron monitor. Photographs of captured or live video images are acquired from a SONY UC-850 video graphic (thermal) printer. The video system uses specialized programming to capture gray tone images for digitizing and numerical analysis. Initial hardware system incompatibility problems consisted of memory conflicts between video cards, capture programming, and the EVEREX tape backup system. These problems were initially resolved by establishing appropriate protocol (programming) to reconfigure the hardware for different applications. Thus the video system runs under its own configuration to resolve its hardware-specific requirements. In addition, high-contrast image problems, resulting primarily from camera low-light over-sensitivity, were resolved through the acquisition of programming that permits control of image contrast outside of the imaging software environment. Subsequently, both the capture board and software (see Task A) were upgraded to take advantage of significantly improved image capture features and extended analysis capabilities. The older capture board will be installed on a different computer and used for macroimaging (discussed below) when laboratory space becomes available with the completion of a current construction project at the EERC.

As developed, the video system can capture images for analysis at three scales or levels of magnification: 1) large or macrosize objects (from 10 to 500 mm in length), 2) small three-dimensional objects (from 1 to 50 mm in length), and 3) very small or microsize, effectively two-dimensional, objects (less than 1 mm in size). Large-scale objects are viewed directly with the Cohu camera system. The camera and attachments are mounted directly to a modified Kodak MP3 copy stand. To facilitate the control of lighting during video photography, the copy stand was rewired so that each of the four high-intensity lamps could be individually regulated. Relatively small specimens, or the closeup study of large specimens, require macrophotography. To achieve the ability to examine samples of this small size, a video-ready Olympus stereomicroscope was acquired and integrated through a coupler to the video camera. This video system provides magnification from about 2.5x through about 50x and was used for image capture analysis and photography of nonmarine mollusks and mammals used in the environmental reconstruction and biochronologic organization of coal strata. Objects of microsize are studied under thin-section with high-powered stereomicroscopes. An EERC Zeiss microscope has been available for the purpose of video imaging of pollen for analysis. A video/microscope coupler, specific to Coal Science imaging research, was manufactured by Diagnostic Instruments to permit video numerical analysis of objects magnified up to 500x.

3.3 Task C—Database Design and Modifications

Several purposes are served by database management procedures. The foremost is the utilization of data in an effective manner. "Effective," however, is relative depending on goals and means of analysis available at a person's disposal. An understanding of coal resources and their litho- and chronostratigraphic context were "effectively" met 70 years ago under the goals of the time. Today's goals are different only in that we require (or want) greater precision in our assessments of resource characterization and context, which necessitates more data more rigorously controlled to serve specific purposes. Resource management is in a state of flux, in part, because the techniques of database management are undergoing a revolution for the individual user due to advances in computer technology and software development. Computer-based data management applications require flexibility (and transportability) while we take advantage of developments in off-the-shelf data acquisition, management, and display programming.

The data management program Q&A® by Symantec is particularly well-suited to the nature of geologic data where 1) a wide range of information types are employed to manage closely related and disparate data types; 2) applications vary, and form and report modifications are made frequently; and 3) extended documentation is necessary to track on inputted numeric and descriptive data. The primary Q&A® form design is more appropriate than a table design employed by most other data managers.

Four main Q&A® databases control NDMMRRI data types: 1) geologic section or observation location information (*MNOS), 2) geologic section unit descriptions (*UNIT), 3) paleontologic specimen location and stratigraphic information (*LOC), and 4) taxon identification information (*SPP). The prefix "*" denotes a specific file name, such as "WB" for Williston Basin. A number of other databases are employed to "feed" basic information to these primary databases. These secondary databases serve several useful functions in promoting control over frequently general (descriptive) information. Examples of secondary databases include EPCODES (chronostratigraphic terminology), FMCODES (lithostratigraphic terminology), COLOR (color coding, as per the Geological Society of America's Rock Color Chart (with Munsell color standards), and MAPS (U.S. Geological Survey 7.5-minute, 1:24,000-scale topographic quadrangles).

The *MNOS files contain information on the location of geologic observations, such as surface and subsurface measured sections. The *MNOS form contains 141 fields, representing four major types of field data: 1) reference information, including numbering systems; 2) location and landowner information; 3) litho- and chronostratigraphic information, including section thickness and elevation data; and 4) sample and specimen information. A detailed description of *MNOS field types, along with examples of forms and data, was presented by Hartman (1992).

The companion file to the *MNOS database is the *UNIT database. Like *MNOS files, a number of *UNIT databases use fields designed for restricted-value internal lookup tables. *UNIT files have 84 fields specific to the reference, measurement, and description of a unit (or bed) in a geologic section. A "unit" is a stratigraphic interval, identified by the geologist, that is sufficiently distinct from lithologies above and below to represent a discrete portion of the overall geologic section. *UNIT databases can be related to *MNOS databases through the creation of derived fields in the Report Module of Q&A®, thus expanding the capability of sorting *UNIT files on additional reference and location information. The majority of the *UNIT fields concern the naming, measurement, and description of unit data. As examples, the unit (bed) name and formational assignment are given also with necessary comments on revised lithostratigraphy. The unit thickness can be directly inputted in English (including nondecimal entries) or metric units, with automatic conversion to respective fields, or the thickness can be calculated from scaled measurements taken from drawings or photographs. Unit thickness can also be calculated from original structural data (e.g., pace and compass method) associated with the measurement of either the unit itself or the section in which it is found). The unit (or bed) description can be quoted in full from the original source and can be separated into its component parts to permit uniform interpretation and sorting on specific data types (e.g., fresh and dry colors, as per the Geological Society of America). *UNIT files use the COLOR and STRATCOL/STRATA files as external lookup tables to import color values and graphic and weathering symbol codes directly into a *UNIT database. Other fields manage information to provide uniform coding procedures for specific projects (e.g., NCRDS data fields) or computer programs (e.g., STRATCOL/STRATA). For example, the *UNIT database is designed to generate reports for the program STRATCOL/STRATA. With only minor modifications, these files can be directly read by STRATCOL/STRATA, thus quickly producing a graphic representation of the geologic unit. A detailed description of *UNIT field types, along with examples of forms and data, was presented by Hartman (1992).

*LOC files contain records on fossil localities and are specifically designed for micro- and macrofossil specimens. The *LOC file is similar to *MNOS files in general design, containing the nearly the same fields for reference and location data. Like the *MNOS form design, *LOC files contain a number of coding fields that are used for sort routines of age-related information and use the MAPS file as an external lookup table for map reference information. Also like *MNOS databases, *LOC databases use fields designed with restricted-value internal lookup tables (see discussion under Q&A® file modifications). *LOC files contain 138 fields organized into the following major field types: 1) reference information, including numbering systems, and a number of specialized fields for record management; 2) location systems, including elevation data; 3) litho- and chronostratigraphic information; and 4) paleontologic data. The *LOC database stratigraphy fields differ from *MNOS databases, in part, in that fields are designed to permit precise reference of a fossil locality to an intra- or extraformational stratigraphic marker or horizon. In addition, a locality can be placed in reference to the base or top of the enclosing formation. Various code fields document the predicted error associated with the placement of a locality relative to any of these horizons. Besides these "relative" stratigraphic fields, the elevation of a locality and its interpreted error can also be inputted. All of these fields can be entered in either English or metric units, with automatic conversion to respective fields. *LOC database fields specific to paleontology are primarily concerned with the record of fossil discovery, collection, and identification. A detailed description of *LOC field types, along with examples of forms and data, was presented by Hartman (1992).

The *SPP database is a companion to *LOC files' and records' detailed information on the identification of taxa from a particular locality. The *SPP database can be used as an external lookup table to combine taxon identifications with stratigraphic and location data. Field types of the *SPP database include 1) taxon identification, 2) a simplified classification of the taxon, 3) repository and specimen numbers, 4) number of specimens, and 5) identification comments. Both old and revised identifications are recorded to provide a history of study on specific specimens and taxon names. *SPP uses the database MCLASS as an external lookup table to extract classification data. With *SPP, *LOC, and MCLASS databases, the stratigraphic range of taxa can be determined through a merge of the data from the three files.

3.4 Task D—Database Input and Augmentation

The geologic exposures of far-western North Dakota are largely derived from the drainage patterns produced by the Little Missouri and Missouri Rivers. The relatively good outcrops along these rivers and some of their tributaries have been the source of many independent coal and noncoal studies. Much of these data has never been assimilated for the purposes of detailed coal correlation, and is, for the most part, not part of any database system. As part of this Coal Science database design and management program for Williston Basin, selected stratigraphic data were cataloged and computerized from data sources relevant to exposures along the Little Missouri and Missouri Rivers in western North Dakota and adjacent areas in the drainage of the Yellowstone and Missouri Rivers in eastern Montana. Input study areas in North Dakota included 1) Bowman, Slope, and western Adams and Hettinger Counties; 2) Billings and Golden Valley Counties; and 3) McKenzie and Williams Counties. These county-based areas represent, to a certain extent, well-defined input data sets, based on the nature of available outcrops and county surface and subsurface studies. The input coverage in the adjacent counties in Montana is less comprehensive, which simply reflects project goals focused in North Dakota. Coverage in Montana included Roosevelt, Richland, Dawson, Wibaux, and Fallon Counties. The stratigraphic data inputted for North Dakota represent primarily the Fort Union Group, which includes the Ludlow, Cannonball, Slope (upper Ludlow of some authors), Bullion Creek (= Tongue River in adjacent Montana), and Sentinel Butte Formations. The following M-number geological observations have been recorded in North Dakota: 1) 609 in Bowman County, 2) 49 in Adams County, 3) 1675 in Slope County, 4) 63 in Hettinger County, 5) 423 in Golden Valley County, 6) 344 in Billings County, 7) 178 in McKenzie County, and 8) 203 in Williams County. In Montana, M-number geological observations have been inputted as follows: 1) 64 in Roosevelt County, 2) 72 in Richland County, 3) 151 in Dawson County, 4) 110 in Wibaux County, and 5) 56 in Fallon County. In addition to these records, geologic observations were also recorded in the Williston Basin of north-western South Dakota and east-central Montana. As part of this research, an annotated bibliography of unpublished and published coal-related observations has been compiled to facilitate computerization (see Hartman, 1992). In total, over 33,000 *UNIT forms were entered as part of the data input and augmentation portion of the Coal Science project.

Although *MNOS and *UNIT information is computer-accessible, data management procedures were facilitated for a number of purposes by the creation of a paper-based "library" of computerized data. This entails, as necessary, the assembly of the original published and unpublished sources of the M-numbered sections (*MNOS and *UNIT databases) and ordering them in a set of (currently 30) ring binders for archival purposes. An archived hard copy system provides a permanent method of verifying the use of the M-number assigned to a particular geological observation.

3.5 Task E—Drilling Project

The drilling and logging of test holes in far-western North Dakota was undertaken to 1) provide fundamental information on data management problems associated with subsurface litho-, bio-, and chronostratigraphic correlation of Paleocene lignite-bearing strata in western North Dakota and easternmost Montana, and 2) determine the most useful means of incorporating, managing, and interpreting the derived information. The two sites chosen were in northwestern Slope County (M2187) and in southwestern Golden Valley County (M2188), North Dakota. The strata represented by these sites include uppermost Cretaceous Fox Hills and Hell Creek Formations and the lower and middle Paleocene Ludlow, Slope, and basal Bullion Creek Formations. One of the sites (M2187) is located in the immediate vicinity of the stratotype of the Slope Formation. Both sites are on U.S. Forest Service property and required permits for access and drilling. As per permit requirements, geophysical and lithic data were submitted to the U.S. Forest Service as part of permit obligations associated with the drilling of two holes in Slope and Golden Valley Counties, North Dakota.

Hole M2187 was drilled through strata of the Slope and Ludlow Formations of the Fort Union Group, the Hell Creek Formation, and into the Fox Hills Formation to a depth of 1040 ft. Hole M2188 was drilled from a higher stratigraphic level, intersecting strata of the Bullion Creek, Slope, and Ludlow Formations of the Fort Union Group and ended in the Hell Creek Formation at a depth of 760 ft. A record of lithic samples and a driller's log were made at both holes. Subsequently, both holes were plugged and restored.

During the course of the drilling activity, two surface sections were measured adjacent to the drill sites (M2252 for hole M2187, and M2253 for hole M2188). These sections were completed specifically to provide control on subsurface interpretation of the geophysical and drill sample record. A detailed comparison was made of the various overlapping portions of these records (see Hartman, 1991a). The primary data associated with drilling project included 1) the driller's record, 2) the lithic log, and 3) the geophysical logs. As a result of the drilling program, minor modifications were made to *MNOS and *UNIT files (designed under the program Q&A® by Symantec). Data from both drill holes were incorporated into geologic cross sections summarizing the coal bed stratigraphy of Slope, Golden Valley, and Billings Counties. Secondary data derived from the drill hole were the palynomorph analyses of "mud" lithic samples. Selected horizons were processed for palynomorphs to derive biochronological and environmental information on the coal-bearing strata associated with the transgressive-regressive events associated with the Cannonball Sea and the coal strata generally marking the Cretaceous-Tertiary (K/T) boundary. Palynomorph and associated sedimentological studies were undertaken by Mr. Timothy J. Kroeger of the University of North Dakota Department of Geology and Geological Engineering (additional discussion under Research Studies).

3.6 Task F—Database Design Assessment and Modifications

The designs of all of the Coal Science databases were assessed and redesigned essentially on a continuous basis. Early changes in *MNOS, *UNIT, and *LOC database designs usually were the result of the determination of the need for a new field based on implementation of a database (as per examples in Task I, Section 3.9) and the drilling project (Task E, Section 3.5) Thus user needs were clearly defined by test case examples indicating what type of data control was required to produce the desired results. The designs of databases were also modified as a result of database augmentation. The need for faster and more accurate methods for data entry produced a number of substantial improvements in both field structure, nomenclature, and associated programming. Many of these improvements would probably not have been developed if relatively large and varied data sets had not been part of the Coal Science program. Many advanced data entry features, such as lookup windows for restricted data entry, required more initial setup on the part of the systems operator, but these efforts were more than repaid by the reduction in subsequent editing of inputted data.

Selected modifications to Q&A® *MNOS, *UNIT, and *LOC databases included the following types of programming statements: 1) referential structure within a database, 2) set initial values, 3) data management of forms, 4) data management of forms between related databases, 5) conversions of various types of numeric data for ease of data entry and reporting, 6) numeric calculations to acquire standard input values, 7) internal lookups for data entry, and 8) external lookups for data entry. "Referential structure within a database" refers to the existence of the appropriate numbering system (e.g., M-number) and reference occurring at the top of each screen (e.g., five screens are used for the *LOC database). "Set initial values feature" refers generally to log-on dates, enterer, or other consistent information for a data set to be entered in a form. This information is automatically entered upon adding a new form to a database. "Data management of forms" refers to date and time fields that automatically record any changes occurring to a particular form. "Data management of forms between related databases" refers to external lookup checks to determine if certain forms or values of importance to related forms in different databases have been entered and/or entered correctly. "Conversions of various types of numeric data" refers to 1) English-metric conversions for elevation, distances from section lines, relative stratigraphic horizons, unit and section thickness; 2) lettered section subdivision (e.g., abcd sec. 2) conversions to legal subdivision (e.g., NE¼ NW¼ SW¼ SE¼ sec. 2); and 3) generalized legal subdivision conversions from given distances from section lines. "Numeric calculations to acquire standard input values" refers to 1) the (automatic) determination of cumulative footages (in *UNIT databases) of geologic sections; 2) the determination of unit or section thicknesses from strike, dip, and pace information (various trigonometric calculations); and 3) the determination (under certain circumstances) of the stratigraphic horizon (such as the bottom of a unit) from other given values. "Internal lookups for data entry" refers to the use of popup windows for the selection and entry of (restricted) field values. Internal lookups of this type have been designed for STRATCOL/STRATA lithic categories, names of formations, crew chiefs, collectors, discoverers, reference citations, institutions, states, field areas, and regions. "External lookups for data entry" refers to the use of external (other) databases to enter specified values into appropriate (programmed) fields. External lookups are used in access quadrangle data (e.g., year, series, contour interval, etc.), color nomenclature, codes for series (epochs), stages (ages), formations, levels, and STRATCOL/STRATA graphic parameters.

Besides the *MNOS, *UNIT, and *LOC file modifications mentioned above, database "form" design modifications were made to a number of Write module output forms. Also, databases, such as SPEC, were constructed for the purpose of controlling data associated with collected samples and for printing collection labels. The greater font control, available with Version 4 of Q&A®, makes possible the printing of the necessarily small form designs and associated data. Multiple copies of appropriate forms (for samples from the same location) are then easily produced in the merge-data portion of the Write module.

3.7 Task G—Geochemical Database Studies

In the context of the present Coal Science program, the purpose of designing a coal geochemical database, or any other similar analysis-type database, was to place such observations into a geologic framework. Thus geochemically oriented data can be integrated with stratigraphic and paleontologic databases to better facilitate the reconstruction of paleoenvironments and produce more definitive coal-related stratigraphic correlations (e.g., coal bed finger printing). Such abilities thus afford a more comprehensive and meaningful interpretation of geologic history. Isolated coal analyses, without geologic context, have limited (almost no) value in providing a means to correlate coal beds and coal-forming environments or to interpret depositional or diagenetic histories.

For the purposes of present database considerations, coal and rock geochemical data were downloaded from a mainframe database constructed for another project by LeFever and Murphy (1983). This data set was chosen because it was originally constructed using mainframe programming for the purpose of posing questions of concern to individuals in coal resource assessment. These databases incorporate standard analytical data (e.g., Btu value, sulfur content, etc.) along with stratigraphic and geographic data. Utilizing Q&A®, *MNOS, and *UNIT files and formats, relatable geochemical databases were designed for 1) geographic, geologic, and bibliographic data; 2) lithologic data; and 3) coal chemistry data (see Hartman, 1992 for discussion of databases and examples). All of the available data, representing several thousand initial observations, were incorporated into the above specifically designed Q&A® databases. Unfortunately, very few chemical observations can be tied to specific stratigraphic sections, let alone their placement relative to specific horizons. The use of the LeFever and Murphy (1983) database clearly illustrates the problems attendant in the taking, recording (in the field), and tracking of geochemical data by earlier coal-oriented projects. A very low percentage of the "coal geochemistry" data can be specifically tied to a specific coal bed or even to a specific point on the ground. Thus much good geochemical data is of immediately limited value beyond its original intent.

3.8 Task H—Data Presentation

Display of information in maintained databases is the most important aspect of database utilization for the research scientist. Database management programs, such as Q&A®, provide a means to show data in various output formats used to organize data for research and general publications, technical reports, presentations, and for the construction of illustrations, tables, and slides. Data are most commonly displayed in tables, as rows and columns of observations, or in forms, depending on the nature of the intended use. In addition, graphical representation of data is particularly important where data are inherently visual (e.g., geologic sections) or numeric (e.g., analyses). Of considerable importance to data visualization is the ease with which the data can be displayed. The visualization of data should be used as a tool in data analysis and not as an end in itself. The more easily data can be viewed, the more likely it will be used as a tool to permit the researcher to make better interpretations.

Along this line of reasoning, a number of modifications were made to the public domain program STRATCOL by Peter Guth (now referred to as STRATCOL/STRATA to denote the substantial number of changes that have been made to the program). STRATCOL/STRATA produces a graphic presentation of geologic logs from Q&A® *UNIT database files. Improvements that have been made to STRATCOL include 1) a more comprehensive and realistic symbol library, maintained as the Q&A® external lookup file STRATCOL; 2) an accurate representation of metric or English scale (at whatever scale chosen); 3) available choices of geologic column width; 4) appropriate column display for either surface or subsurface sections; 5) two columns for unit annotations; and 6) elimination of restrictions on input file size and scale selection. Through the use of Q&A® and STRATCOL/STRATA, a graphic representation of a geologic column can be produced with a laser printer in a matter of a few minutes. Several hundred stratigraphic columns were produced at a variety of scales for numerous purposes through the course of Coal Science studies (see, for example, Hartman, 1991a).

A dual base map system was also developed to display and document Coal Science project data for detail and general purposes. Geological and paleontological observations in *MNOS and *LOC databases were plotted on U.S. Geological Survey (USGS) 1:100,000- and 1:24,000-scale topographic maps covering far-western counties of North Dakota and adjacent areas in Montana. Most locations were plotted on linen-backed mosaics of 0.5° x 1°, 1:100,000 topographic quadrangles for general display purposes. These mosaics were constructed to best reflect the likely distribution of data for certain study areas, including 1) the Fort Union corridor of Williams and McKenzie Counties, North Dakota, and Roosevelt and Richland Counties, Montana; 2) the northern portion of the Little Missouri River, McKenzie County, Montana; 3) the main north-south drainage system of the Little Missouri River in Billings and Golden Valley Counties, North Dakota; and 4) additional natural outcrop and subsurface study areas in Slope and Bowman Counties, North Dakota. Large-scale maps (i.e., 1:24,000 scale) have both utility for both display and documentation of location and topographic information. Note that many coal-related observations were originally collected without regard to elevation. Plotting on large-scale topographic maps provides the opportunity, given the nature of the observations, to closely approximate the elevation of a particular observation. Such controlled information is of considerable importance in attempting to correlate and contour a variety of geological data types. These maps can also be used as the basis for digitizing coal and related geological observations for use in geographic information system programming and geologic software.

In addition, numerous Q&A® Write module form reports were implemented throughout the course of Coal Science studies. These reports constitute a combination of primary text and merger of information from selected databases (for examples, see Hartman, 1992). Write module forms provide an additional means of cataloging selected data into whatever project-specific format is appropriate. Effectively, databases can be redesigned to meet any display need without affecting the primary form of the database file.

3.9 Task I—Database Implementation

Implementation or utilization of a database is the best means to realize the requirements for its effective use. Field, laboratory, and computer-based activities have greatly facilitated the diverse requirements for the construction and revision of Coal Science database systems. The use of databases as tools in research, rather than as a means simply to gather data for the purposes of generalization, provides a much more rigorous basis for testing their design and utility. A few selected projects are discussed in the following section (see the section on Information Dissemination for a comprehensive list of projects utilizing Coal Science databases). In addition, I have included graduate and undergraduate student projects that have substantially benefitted from Coal Science databases. These projects included sedimentologic, lithostratigraphic, biochronologic, and paleoenvironmental research directed towards establishing a more rigorous basis of interpreting the coal-bearing strata of the northern Great Plains.

Research was undertaken in preparation of a manuscript with Dr. Alan Cvancara of the University of North Dakota Department of Geology and Geological Engineering on the "Paleocene Stratigraphy and Molluscan Paleontology of the Cannonball (Brackish) and Ludlow (Nonmarine) Formations in Southwestern North Dakota." This work represents the essence of coal-based data management for the purposes of coal correlation. The above project represents the correlation of coal-bearing strata of the Slope (Ludlow of some authors) Formation in southern Golden Valley and Slope Counties, southwestern North Dakota. This work summarizes the stratigraphic occurrence of coal-bearing strata relative to the occurrence of brackish water and freshwater fossils. All of the 110 plus sections and isolated geological observations are managed in Q&A® databases and have been graphically illustrated through modifications to the program STRATCOL/STRATA developed over the last one and a half years. On the basis of the stratigraphic framework 1) revised coal correlations has been proposed, 2) coal bed nomenclature has been revised, 3) the distribution of the tongues of the Cannonball Formation has been graphically illustrated, 4) the tongues of the Cannonball Formation will be formally named, and 3) the stratigraphic distribution of over 150 fossil localities has been plotted, providing a temporal and environmental context for interpreting the geologic history of the area. This work permits the construction of coal isopach and structure contour maps for the area. This study thus provides a foundation for the stratigraphic and paleoenvironmental interpretation of lower and middle Paleocene coal-bearing strata in southwestern North Dakota.

Research presented at an annual meeting of the Geological Society of America (GSA) summarized research conducted on the stratigraphy and molluscan paleontology across the Cretaceous-Paleocene boundary in the northern Great Plains (Hartman, 1991b). Information utilized in the preparation of this paper was derived from databases maintained in Q&A® for the Williston, Powder River, and Crazy Mountains Basins in the northern Great Plains of the United States and Canada. Research delimited the occurrence of certain taxa through the uppermost Cretaceous Hell Creek and Lance Formations and Paleocene Ludlow, Tullock, and Bear Formations, providing biochronologic control for temporal correlations across North Dakota, Montana, Wyoming, and Saskatchewan.

A publication with Dr. Allen J. Kihm of Minot State University was presented as a poster session at the Sixth International Williston Basin Symposium (and Fourth Saskatchewan Petroleum Conference) in Regina, Saskatchewan. This paper concerned the stratigraphic and biochronologic context of pantodonts (vertebrates) in North Dakota. By more rigorously defining the stratigraphic and geographic position of a number of localities, the stratigraphic distribution of this group has been shown to be more temporally restricted than previously understood. This type of information permits more precise temporal (biochronologic) correlation of the coal-bearing strata of the upper Bullion Creek (Tongue River of some authors) and Sentinel Butte Formations. All of the stratigraphic and paleontologic data used to construct this paper and associated figures were organized through Q&A® databases developed and tested through Coal Science field and laboratory research.

Collaborative research, undertaken with Dr. David Krause of the State University of New York at Stony Brook, has resulted in a number of ongoing projects concerning the temporal organization of coal-bearing strata in the northern Great Plains. Such information bears on the development of an understanding of the chronology of the Cretaceous/Tertiary transition, representing a shift in paleoenvironments from noncoal to coal-dominated settings in this area and in the timing of the advances and retreats of the Cannonball Sea and associated coal-forming environments.

Research of T.J. Kroeger. Mr. Kroeger, a Ph.D. candidate in the University of North Dakota Department of Geology and Geological Engineering, undertook dissertation studies entitled "Paleoecology of Palynomorph Assemblages in the Upper Ludlow Formation (Paleocene), Southwestern North Dakota." Mr. Kroeger's research has made extensive use of Q&A® Coal Science databases, including the *MNOS and *UNIT databases, as well as others that have been specifically designed for sample record keeping in the laboratory and as accession records into the collections of the University of North Dakota. Mr. Kroeger is in the process of analyzing and interpreting the palynomorph-bearing sediment samples for brackish and marine indicators to provide greater resolution in interpreting these environments in the western Slope and southwestern Golden Valley Counties, North Dakota, and in Dawson County, Montana. In addition to his dissertation studies, his research has identified the Cretaceous-Tertiary boundary in surface and subsurface samples in Slope County, North Dakota, and in surface samples from Makoshika State Park, Dawson County, Montana. This information will be used in conjunction with age information interpreted from the nearby Hiatt mammal locality for the purposes of establishing a chronostratigraphic framework for the transition between largely nonlignite-bearing to lignite-bearing strata along the Yellowstone River and elsewhere.

Research of W.D. Peck. Mr. Peck completed his Master of Science degree in the Department of Geology and Geological Engineering at the University of North Dakota. His project was entitled "The Stratigraphy and Sedimentology of the Sentinel Butte Formation (Paleocene) in South-Central Williams County, North Dakota." Mr. Peck made extensive use of Q&A® *MNOS and *UNIT databases for his stratigraphic and sedimentologic studies. As a part of current related studies, Mr. Peck, with Dr. Allen J. Kihm and this writer, has attempted to construct a coal-based correlation framework for the area between the Nesson Anticline and Fort Union. This effort utilizes the relatively numerous isolated reports of coal along the Missouri River that have been computerized into *MNOS and *UNIT databases. Aspects of our study were incorporated into Mr. Peck's thesis research.

Research of M.M. Rolland. Ms. Rolland has undertaken a senior thesis project, under this writer's supervision, in the Department of Geology and Geological Engineering at the University of North Dakota. The project is entitled "A Faunal Comparison of Selected Freshwater Mollusks from the Upper Cretaceous (Edmontian?) Fruitland Formation of the San Juan Basin, New Mexico, with the Hell Creek Formation (Lancian) of the Williston Basin, Montana-North Dakota." Ms. Rolland's study involves the paleontologic and stratigraphic study of nonmarine mollusks from the coal-bearing strata of the Williston Basin of North Dakota and Montana and the San Juan Basin of New Mexico. Research will be directed towards understanding the evolutionary history of selected nonmarine molluscan taxa to provide a more rigorous biochronologic framework for the correlation and paleoenvironmental interpretation of nonmarine strata in the Upper Cretaceous strata of the western interior of the United States. Studies to date have utilized Coal Science data management systems (i.e., *LOC database) to revise geologic and paleontologic data concerning relevant strata in North Dakota.

4.0 FUTURE STUDIES

Coal Science data management research effectively represents an ongoing process of development and utilization. The Coal Science database management system serves and can serve in the future as 1) a means of tracking coal-oriented geologic data, regardless of current project needs; 2) a means of utilizing these data for projects that can be specifically generated within the framework of established or possible Q&A® database programming; and 3) a front end for generating information in a format acceptable to other programs that may inherently not be well suited for data management (e.g., various types of graphics, or modeling, mapping programs). The approach taken in the Coal Science program has shown considerable success in all aspects of the three avenues of future studies given above. In almost all ways, these uses of Coal Science database management research are mutually compatible and necessary pathways to productive and rigorous use of any and all geographically and stratigraphically oriented coal data.

5.0 SUMMARY AND CONCLUSIONS

The general Coal Science objective of the EERC NDMMRRI was directed towards more effective and efficient use of geologic observations specific to the correlation and assessment of coal-bearing strata. The utilization of these observations required streamlined but flexible user-oriented data management programs that incorporated straightforward data inputting and output in the form most convenient for the user. Substantial amounts of currently useful and historically invaluable geologic data bearing on the correlation of coal beds are available for most coal-bearing areas. This is certainly the case in the lower Tertiary strata of the northern Great Plains in general and in western North Dakota specifically. This information exists as published and unpublished but accessible documents. The specific objective of this project was to implement, through computer-based data management systems, site-specific test-case field studies that utilized all currently available information for the assessment of efficient database management techniques in the evaluation of specific coal correlation problems. This project was fundamental to coal resource and geologic studies undertaken by the EERC. By its very nature, the Coal Science project has been unique in its blend and utilization of 1) historic and current coal-oriented geologic observations, and 2) in its use of litho-, bio-, and chronostratigraphic data to forge a geologic framework for refined coal correlation. The approach has been multidisciplinary and aimed at resolving specific questions beyond the scope of narrowly focused vested interests.

The focus of the first phase of this project was to establish the computerized basis for reevaluating North Dakota's lignite resource in a stratigraphic and paleontologic context. The goal of the second phase of the project was to establish realistic database case studies, including surface and subsurface data specifically taken with the design and construction of stratigraphic and paleontologic databases as a resulting product. The third phase was to set new and greater demands on the stratigraphic database design. Several thousand surface and subsurface data entries have been compiled from the uppermost Cretaceous and Paleocene Fort Union coal region of the Williston Basin, including far-western North Dakota and adjacent easternmost Montana. Database designs have continued to be modified to reflect a greater knowledge on the demands and needs of the end user. Unlike other databases that are constructed to summarize the data compiled, database research under the Coal Science program has attempted to design a flexible data management system that serves an ongoing interactive need to answer previously unconsidered resource-based questions.

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4.0 COMBUSTION RESEARCH

4.1 Atmospheric Fluidized-Bed Combustion

ATMOSPHERIC FLUIDIZED-BED COMBUSTION

Final Technical Progress Report
for the Period April 1, 1986, through December 31, 1992

by

Michael D. Mann, Research Supervisor
Ann K. Henderson, Research Engineer
Thomas A. Moe, Research Engineer

Energy and Environmental Research Center
University of North Dakota
P.O. Box 8213, University Station
Grand Forks, North Dakota 58202-8213

Task Contracting Officer's Representative: Dr. Art Hall

for

United States Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
3610 Collins Ferry Road
P.O. Box 880
Morgantown, West Virginia 26507-0880

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FLUIDIZED-BED COMBUSTION OF LOW-RANK COALS

1.0 BACKGROUND

The main driving forces behind the use of fluidized-bed combustion have primarily been environmental concerns, fuel flexibility, and compatibility with low-cost fuels. Both bubbling and circulating designs have been developed for operation at atmospheric pressure, and many industrial-scale units of both types are currently in operation. A limited number of larger utility boilers have recently been commissioned. In addition, pressurized fluidized-bed combustion (PFBC) is making its entrance on the utility scale with the PFB installed at the Tidd Station.

Even though fluidized-bed combustion technologies are being commercialized, a number of areas require further research. An integrated approach should be taken toward fluidized-bed combustion research, interrelating those problems generic to bubbling, circulating, and pressurized fluidized-bed combustion systems. The program should also be designed to address specific problems related to each of these areas. Major issues facing fluidized-bed combustion are listed below:

- Methods are needed to minimize corrosion and erosion of in-bed and convective pass tubes, refractory and support surfaces, and expander turbines. Work should focus on the following:
  - Understanding mechanisms involving
    - Mineralogical properties of the bed and coal
    - Fluid mechanics of the bed
    - Corrosion versus erosion
    - Stress forces on tubes
  - Assessing acceptable wastage levels
  - Identifying cost-effective methods of combating tube wastage
  - Developing systematic test devices

- Retrofit applications should be addressed for all types of FBCs. According to information from the American Boiler Manufacturing Association (ABMA), approximately 200 existing units are candidates for retrofit technologies. The FBC retrofits at Northern States Power's (NSP) Black Dog Station, Montana-Dakota Utilities (MDU) Heskett Station, and Colorado Ute's Nucla Station have demonstrated the feasibility of such applications.

- Fuel flexibility and characterization issues should be addressed to help users understand constraints of fuel switching, design considerations, and, most importantly, the economics involved in having fuel flexibility for the FBC.

- Agglomeration/sintering of bed material and deposition on tubes, support surfaces, and refractory, has been identified as a problem by both manufacturers and users of FBC technology. Problems have been documented for both bubbling and circulating beds, using a variety of fuels, including coal. The University of North Dakota Energy and Environmental Research Center (EERC) has extensive experience in this area to help understand and solve this operational problem.

- Scaleup effects need to be addressed so that vendors and users can take pilot-scale data and be assured that the large-scale system will perform as anticipated. This database has been growing rapidly with all of the new units starting operation; however, much information is still required.

- Advanced systems should be designed to resolve problems and improve overall FBC performance. These systems should:

  - Increase volumetric heat release rates.
  - Improve overall boiler efficiency.
  - Simplify fuel feed and ash removal systems.
  - Decrease capital and operating costs.
  - Improve turndown.
  - Decrease the size of units to enable modular construction.

- Several problems related to emissions from FBC systems need to be addressed:

  - Better sorbent utilization would improve the economics of FBC.

  - NO_x control is currently not a major problem, but could become more difficult with bubbling beds if standards become more stringent.

  - Information indicates that particulate control problems may exist for certain types of ash. These ashes should be identified, and specific equipment and conditioning of other methods should be applied to resolve the problem.

  - Hot-gas cleanup is required for PFBC to meet turbine specifications, in addition to new source performance standards (NSPS).

These problems and concerns could limit FBC from reaching its full potential. Special efforts should be taken to perform the necessary research to help FBC evolve to a mature technology, meeting the technical, economic, and environmental needs of the future.

2.0 OBJECTIVES

A number of major issues have been identified that warrant further research. The EERC has the capability to investigate several issues in bubbling atmospheric fluidized-bed combustion (AFBC). Some of these issues are proposed in this work plan. Other FBC research should be funded, at least partially, by the industrial sector, either through Electrical Power Research Institute (EPRI) or private companies. Efforts should continue to transfer the expertise gained under previous Cooperative Agreements to the private sector.

The overall goal of the low-rank coal (LRC) FBC program at the EERC is to develop a technology database so that industry can introduce economically and environmentally acceptable coal technology options to the marketplace. Research will address those areas where data gaps exist in fuel flexibility and performance, potential operating problems, environmental compliance, advanced concepts, and system simplification.

3.0 CHARACTERIZATION OF COALS

The main purpose of the coal characterization portion of the program was to examine the differences that exist between different coals, both as a function of rank and as a function of ash properties independent of rank, and to relate these differences to the design and performance of an AFBC. Knowledge of specific properties is critical in the design phase, while an understanding of other properties is more critical during operation. The information presented here was obtained from the published literature and is supported with test results generated on the pilot-scale AFBC test facilities at the EERC. Since all of the data was generated with different fuels burned in the same unit, the differences in performance should be a clear depiction of the effects of coal properties, independent of system design. A summary of the effects of coal properties on AFBC system design and performance is presented in Table 1.

3.1 Comparison of Coal Properties

Coals are ranked based on established ASTM guidelines, according to their heating value, amount of volatiles, and fixed-carbon content. The low-rank coals are characterized as having low heating value, high volatile content, and high moisture. Conversely, the higher-rank coals are characterized by high heating values and a high fixed-carbon content. Generally speaking, the reactivity of the fixed carbon, or char, increases as rank decreases.

The quantity and nature of ash can vary widely, and is more a function of the region of the country and the geological conditions under which the coal was formed, rather than a function of rank. Many western coals have relatively high alkaline content as compared to their eastern counterparts; however, many of the coals in the Southwest have several of the same ash components as typical eastern coals. Sulfur, another critical coal property, is also more dependent on location than on rank, although most eastern coals have higher sulfur contents than do western coals. Therefore, when comparing the effects of coal properties on AFBC performance, it is critical to compare performance based on individual coal parameters, independent of rank.

The EERC has built an extensive database characterizing the performance of a variety of coals of all ranks. The analyses of these coals are shown in Table 2.

3.2 Description of Equipment

A bubbling AFBC design was used for the evaluation of the general system effects described here, and all pilot-scale work was performed in the bubbling mode. The system consists of:

TABLE 1

Effects of Coal Properties on AFBC System Design and Performance

Coal Property	Effect on System Requirements and Design	Effect on System Thermal Performance	Effect on System Environmental Performance
Heating Value	Determines size of feed subsystem, combustor, particulate collection equipment, and hot duct.	Efficiency impacted by moisture and ash content (see below).	Size of particulate collection devices.
Moisture Content	Can impact feed system design and capacity and size of convective pass.	Higher moisture lowers thermal efficiency.	Very high moisture can increase CO emissions due to afterburning.
Ash Content	Determines size and type of particulate-control subsystem and size of ash-handling subsystems.	Higher ash lowers thermal efficiency via heat losses from hot solids removal.	None, with proper design.
Volatiles/Fixed Carbon Content	Impacts fuel feed method.	Lower combustion efficiency for fuels with low V/FC content.	None, with proper design.
Sulfur Content[a]	Determines required capacity of sorbent subsystem and ash-handling subsystem. Higher sulfur usually dictates use of solids recycle.	Higher sulfur can lower thermal efficiency via heat losses from added solids for SO_x control (see ash content above).	None, or proportional,[b] if regulated by site and system size. Determines SO_2 emissions (in conjunction with alkaline ash) if uncontrolled.
Nitrogen Content	None, with common designs and typical regulations.[c]	None, with common designs.[c]	Impacts NO_x emissions.
Chlorine Content	Can impact selection of materials for cool end components. May cause higher corrosion rates of in-bed tubes.	Typically none. Very high chlorides can lower thermal efficiency by requiring operation at higher exhaust temperatures.	Impacts HCl emissions.
Alkaline Ash Content	Can reduce size of sorbent subsystems.	None.	Higher ash alkalinity lowers uncontrolled SO_x emissions.
Sodium and Potassium Content	High sodium can dictate fouling prevention measures and allowance for agglomeration (e.g., soot blowing, frequent bed draining).	Higher sodium can lower thermal efficiency via tube fouling and heat losses from more frequent hot solids removal.	Higher sodium lowers uncontrolled SO_x emissions. Sodium tends to reduce fly ash resistivity for ESP performance improvement; may also enhance fabric filter performance.
Ash Fusibility	Low-fusion temperatures can impact design, due to allowance for fouling and agglomeration potential.	Lower fusion temperatures impact thermal efficiency in the same way as higher sodium.	Typically none.

a The forms of sulfur can have an impact, with high pyrite content requiring longer gas residence time in the bed. The result may be increased operating pressure and blower capacity.

b Sulfur content can determine SO_x emissions, depending on which regulation applies (e.g. NSPS regulations stipulate fractional removals).

c For low-NO_x regulations, a staged combustion or postcombustion NH_3-based suppression design may be required. Staged combustion designs can have higher CO emissions. Postcombustion NO_x suppression subsystems can lower the thermal efficiency slightly and do emit NH_3.

TABLE 2

Analyses of Coals Used in EERC Comparative Study

Coal Name:	Gibbons Creek	S. Hallsville	Beulah	Sarpy Creek	Navajo	River King #1
Source:	Texas	Texas	N. Dakota	Montana	New Mexico	Illinois
Formation/Field:	Jackson	Wilcox	Fort Union	Tongue River	Fruitland	Herrin #6
Region:	Gulf Coast	Gulf Coast	Great Plains	Powder River	San Juan Basin	Illinois Basin
Rank:	Lignite B	Lignite A	Lignite A	Subbituminous B	Subbituminous A	High Vol. C Bituminous
Proximate Analysis, % As-Fired						
Moisture[a]	32.9	29.1	23.2	24.2	13.4	7.3
Ash	25.0	12.4	10.8	10.0	21.2	20.3
Volatile Matter	25.3	29.5	31.0	28.6	29.6	29.8
Fixed Carbon	16.8	28.9	35.0	37.2	35.7	42.6
HHV, Btu/lb	5026	7268	8037	8843	8771	9724
Ultimate Analysis, % Dry Basis						
Carbon	41.9	58.6	62.2	65.6	56.6	54.1
Hydrogen	3.8	4.6	2.7	4.5	4.3	4.6
Nitrogen	0.6	1. 6	0.8	0.8	1.1	1.0
Sulfur	2.2	1.7	3.0	0.8	0.8	3.8
Oxygen	13.6	16.6	17.2	15.1	12.5	16.1
Chlorine	--	0.02	--	0.02	0.03	--
Ash	37.9	17.5	14.1	13.2	24.6	20.3
Ash Analysis, % of Ash						
SiO_2	62.0	38.0	28.5	33.0	59.4	50.5
Al_2O_3	18.5	16.0	8.1	19.2	27.1	18.5
Fe_2O_3	3.6	12.0	9.9	4.1	4.1	14.1
TiO_2	1.0	1.2	1.1	1.1	1.2	1.0
P_2O_5	0.2	0.5	0.9	0.9	0.2	0.6
CaO	6.2	13.0	15.4	20.4	2.6	5.4
MgO	1.4	3.9	5.7	3.3	1.5	1.8
Na_2O	0.5	0.2	4.0	2.9	1.4	0.8
K_2O	0.8	0.9	0.2	0.4	1.0	2.7
SO_3	5.9	14.8	26.2	14.7	1.8	4.8
Calculated Values						
Ca/S Molar Ratio	0.61	0.76	0.89	1.92	0.46	0.16
Na/S Molar Ratio	0.04	0.01	0.30	0.25	0.22	0.02
A[b]/S Molar Ratio	0.65	0.78	1.39	2.17	0.68	0.19
Base/Acid[c]	0.2	0.5	1.1	0.6	0.1	0.4
FC[d]/Volatiles	0.7	1.0	1.1	1.3	1.2	1.4

[a] As-mined moisture levels are higher for several of the coals tested.
[b] Ca + Na.
[c] (Fe + Ca + Mg + Na + K) / (Si + Al + Ti).
[d] Fixed carbon.

- Fuel feed--screw-feed underbed or gravity-feed overbed.

- Sorbent/additive feed--solid sorbent was either fed separately, via gravity-fed overbed pipes, or premixed with the coal.

- Combustor--heat-exchange tubes in the bed, on-line bed draining capabilities, and with or without recycle subsystem for recycling elutriated solids/ash back to the combustor via cyclone and pneumatic reinjection.

- Particulate control--multicyclones/cyclones, baghouse, and electrostatic precipitator, alone or in combination, followed by a stack.

- Associated equipment, such as: blowers, fans, pumps, hoppers, bins, tanks, ash conveyors, instruments, and controls, to permit operation of the system.

The typical operating ranges of the EERC pilot unit for these tests were 1400° to 1700°F combustor-bed temperature, 4- to 9-ft/sec superficial gas velocity, 17- to 26-inch static bed depth, ash recycle ratio of 0.0 to 1.0, sorbent add rates of up to 5.5 alkali-to-sulfur ratio, and 0.5 to 2 second gas residence time. Detailed descriptions of the EERC AFBC test facilities are provided elsewhere (1,2).

3.3 Thermal Performance

In comparing the properties of some common solid fuels, the lignitic and subbituminous coals fall between the high carbon content and heating values of the higher-rank fossil fuels and the more reactive, high-volatile content biomass. Reactivity of the low-rank coals is related to porosity and surface area, volatiles-to-fixed carbon ratio, partially oxygenated organic structures, and catalytic effects of metallic cations within the coal structures. Thus the lower-rank coals will burn more completely and more rapidly than will a bituminous coal under similar operating conditions. Higher reactivity gives greater combustion efficiency, as measured by carbon conversion. Typical combustion efficiencies for low-rank coals range from 95% to over 99% in an AFBC, even without solids recycle, while bituminous coals typically have lower combustion efficiencies (3,4). Combustion efficiencies for all coal types are greatly improved with ash recycle.

As the bed temperature increases, more carbon is burned out in the bed and combustion efficiencies increase. This is true for all the coals tested. At the higher bed temperatures, differences in carbon burnout between the various types of coals decrease.

Thermal performance is also influenced by the amounts of moisture and ash in the fuel. About 1000 Btu are required to evaporate each pound of water entering with the feed coal. Since low-rank coals contain higher levels of moisture than do bituminous coals, more heat is lost during the combustion of low-rank coals as a result of evaporation. When operating at a specific temperature and excess air, the high-moisture, low-rank coals generate increased mass flows through the system per delivered Btu than the lower-moisture coals, resulting in a higher fraction of the energy being recovered in the downstream convective pass heat recovery unit. The overall system thermal efficiency is reduced due to greater stack losses for the high-moisture coals. Overall system thermal efficiency is also reduced by heat loss in the discharged ash of high-ash coals. Unrecoverable heat losses due to moisture effects were as high as 10.4% for the Gibbons Creek lignite, but only 3.8% for the River King bituminous. Heat losses due to ash and spent sorbent are much lower and depend on the total ash content of the coal relative to its heating value and sorbent requirements needed to meet NSPS. System efficiency can be improved by beneficiation of the coals and by ash removal and drying before combustion, but any modifications to improve coal quality would need to be determined before the design of the combustion system to take full advantage of the improvements.

Coal rank will have an effect on the initial design of an AFBC and the operation of an existing system. For example, a system designed for a low-rank coal would require a larger fuel feed system to generate the same amount of steam or electricity as a unit designed for a bituminous coal. Downstream heat transfer area would have to be greater for higher-moisture fuels to account for the higher flue gas flow rates due to the moisture. Units designed for bituminous coals would likely be required to utilize ash recycle to obtain acceptable levels of carbon burnout, while carbon burnout of many of the more reactive lower-rank coals are acceptable without recycle.

3.4 Environmental Performance

Emissions from an AFBC operating with a given coal can generally be controlled using proper system design and operation. While system requirements are dependent on coal properties, the actual emissions are dependent on the system design and operation. It is currently possible to meet all present or proposed national standards with state-of-the-art AFBC technology.

3.4.1 Sulfur Oxide Emissions

While firing coals in an AFBC, the amount of sulfur captured is primarily determined by the total alkali-to-sulfur ratio. The alkali (predominantly calcium and sodium) is provided by the mineral matter and cations contained within the coal and any added sorbent. The forms of alkali occurring in the coal and combustor operating conditions, especially temperature, are also important. Once the coal and sorbent properties are known, system design and operating specifications can be set to achieve virtually any level of sulfur capture. Although theoretical sulfur captures approaching 100% are possible, only 90% to 95% capture is considered economical (5). This is more than adequate to meet current NSPS.

The quantity of available alkali, from the coal itself or added sorbent, largely determines the sulfur oxide emissions generated from an AFBC. Most coals have some alkali in the ash material or as cations in the organic structure that is available for sulfur capture. Inherent alkali-to-sulfur ratios ranged from 0.2 for River King bituminous coal to 2.2 for Sarpy Creek subbituminous coal. This inherent alkali accounted for sulfur retentions of up to 55% in the case of the Beulah lignite and as low as 5% for the River King coal under optimal conditions. The optimal conditions for maximum sulfur capture vary with coal.

Although the total amount of alkali is indicative of how much sulfur capture to expect, it is the degree of availability of the inherent alkali and total sulfur in the coal that really determines the rate of sorbent alkali addition required to meet a particular emission standard. The form of the alkali has a significant effect on its ability to capture sulfur. Alkali utilization is a function of a variety of coal and sorbent properties. Coals in which the alkali is tied up predominantly as cations in the coal structure exhibit higher levels of alkali utilization than do those in which the alkali exists in the mineral matter of the extraneous coal ash. This is because of the more rapid release of the organically bound alkali, and its more intimate contact with the SO_2 that is formed during combustion. The alkali utilization for coals containing a high ratio of organically bound alkali is much better than for those with a low ratio. Another factor affecting utilization of inherent alkali is the base-to-acid ratio. Those coals with a relatively high basic content have available alkali and a high driving force for sulfur capture. However, the sulfur must compete with silicates and other acidic components for available alkali in those coals with a low base-to-acid ratio.

The optimum bed temperature resulting in maximum sulfur capture varies somewhat with coal type. Bituminous coals tested at the EERC and by other researchers (6) show optimal sulfur capture at a bed temperature of approximately 1550°F. Most of the low-rank coals tested, however, exhibit maximum sulfur capture at temperatures approximately 100°F lower. This is partially due to the coal structure and the forms and relationships of the sulfur and alkali in the coal itself. For the low-rank coals, the optimal temperature shifts upward with the use of ash recycle and approaches 1550°F at high ash recycle and sorbent addition rates.

In specifying design and operating conditions for an AFBC, it is critical to know how much sorbent addition is required to meet applicable emission standards. This can vary greatly with coal and sorbent types. For the coals tested, in order to retain 70% sulfur in the bed, the required alkali-to-sulfur ratio ranged from 1.7 to 4.4, depending on coal type. Looking only at the alkali-to-sulfur ratio, however, can be misleading. For example, although an alkali-to-sulfur ratio of 4.4 is required to meet 70% sulfur retention for Navajo subbituminous, compared to 2.5 for the River King bituminous, the total amount of sorbent added for the Navajo was much less, 5.9% of the coal feed compared to 18.5% for the River King, due to difference in the levels of sulfur and alkali in the coals. Emissions standards vary with coal type and typically range from 70% to 90% retention. Additional sorbent would be required to meet more stringent requirements.

When designing a new unit, or when considering fuel switching with an AFBC, it is important to understand the characteristics of the coal and sorbent to be used. As pointed out here, the alkali-to-sulfur ratio will have the greatest impact on sulfur retention and emissions. However, the required alkali-to-sulfur ratio will depend greatly on fuel properties. Likewise, the utilization of sorbent alkali can vary greatly between sorbents, and have a significant effect on the amount of sorbent addition required. It is, therefore, recommended that new designs or new fuels be based on either pilot plant testing of each specific fuel/sorbent combination or operating data from an existing unit burning that or a similar fuel.

3.4.2 Nitrogen Oxide Emissions

The only emissions which are significantly affected by fuel properties (beyond the effects of system design and operation) are nitrogen oxides. The level of NO_x emissions is determined by the coal nitrogen content and by the ratio of nitrogen content to large organic char-forming structures (7,8). Testing at the EERC indicates that although nitrogen emissions are somewhat dependent on total nitrogen in the coal, a better correlation exists between the percent of fuel-bound nitrogen converted to NO_x and the nitrogen content of the coal on a dry ash-free basis. For all the coals tested, the NO_x emissions increased with increasing bed temperature and increasing excess air.

Nitrogen oxide emissions from AFBC are inherently low, and experimental work and experience from operational AFBC facilities have indicated that NO_x emissions beyond the low thermal NO_x "background" levels can be controlled by the proper design and operation (e.g., staged combustion) of AFBC systems. This indicates that AFBC systems may not be limited by fuel nitrogen content, and that the fuel properties only determine the system requirements to achieve the desired level of NO_x emission control. There are also several types of NH_3-based postcombustion NO_x suppression subsystems which can be applied to AFBC systems if further reduction of NO_x emissions is required. This indicates that, although for a specific design and operating scenario NO_x emissions are fuel-specific, the emissions can be controlled within a given range by proper design and operation.

3.4.3 Particulate Emissions and Characterization

In the fluidized-bed combustion process, coal is burned in a bed of noncombustible material. This noncombustible bed consists of some combination of coal ash, added sorbent for SO_2 capture, and/or another selected inert material. A significant portion of the bed material is generally entrained with the flue gas leaving the combustor and must be collected by particulate control equipment. The particulate matter entrained from an AFBC has different physical and chemical properties than fly ash generated in a conventional pulverized coal combustor due to the lower temperature at which an AFBC is operated and because of the sorbent or inert bed material entrained along with the coal ash in the AFBC flue gas. These chemical and physical differences, as well as potentially higher particulate concentrations, will affect the design and operation of the final particulate control device, whether it be a fabric filter or an electrostatic precipitator (ESP).

When considering the use of a fabric filter as the final collection device for FBC particulates, two important considerations arise. The first is control of pressure drop at reasonable air-to-cloth ratios. Studies performed outside the EERC have shown that higher tube sheet pressure drops are observed when collecting FBC fly ashes than when collecting pulverized coal fly ashes at the same air-to-cloth ratios (9). The second important consideration is the collection efficiency of fabric filters when collecting FBC particulates. The collectibility of several coals has been evaluated at the EERC using a baghouse with woven glass bags. Though particulate collectibility was not the primary focus of the pilot-scale combustion studies, some general comparisons can be made for the coals tested. A general trend of increasing collectibility with increased pressure drop (caused by a buildup of fly ash dust cake on the bags) was observed. More importantly, significant differences are seen in the relative collectibility of FBC fly ashes from various coals. Collection efficiencies greater than 99.0% were observed for the River King and Sarpy Creek coals. However, efficiencies dropped off significantly for the Navajo and Gibbons Creek fly ashes, ranging from 97.5% to 98.0% for the Navajo, down to 92.8% to 97.0% for the Gibbons Creek fly ash. Particulate emissions ranged from a low of 0.0015 lb/MM Btu for one of the River King tests to greater than 0.30 lb/MM Btu for some of the Gibbons Creek tests, which is significantly higher than the 1979 NSPS limit of 0.03 lb/MM Btu. This data indicates that differences exist in the collectibility of various AFBC fly ashes, and care must be taken in choosing the proper air-to-cloth ratio, bag material and weave, number of compartments (affects increase in ΔP during cleaning), use of sonic horns, and type of baghouse to ensure adequate particulate removal.

To evaluate the potential effectiveness of ESP systems collecting FBC-generated particulates, laboratory measurements have been made at the EERC on composite samples of fly ash collected during pilot-scale fluidized-bed combustion tests with several coals. The laboratory resistivity measuring apparatus used allows simulation of the actual flue gas conditions encountered during the combustion tests. Measurements made on fly ashes collected from baseline tests (inert bed material without ash recycle or sorbent addition) with several coals indicates that, while there is much variability in fly ash resistivity based on chemical composition, there was not a significant difference between FBC ash resistivity and that of fly ashes generated in a conventional pc-fired unit. The addition of sorbent can greatly increase the resistivity of FBC fly ash by changing the chemical composition. Large increases in resistivity with limestone addition were observed for the Gibbons Creek lignite, but were not as evident for the Navajo and Sarpy Creek coals. The effect of ash recycle on fly ash resistivity appears to be relatively insignificant.

3.5 Bed Material Agglomeration

Uniformity of AFBC bed conditions is maintained by the active nature of the suspended particles within the size range compatible with the velocity of rising gases. When particles within the bed grow in size due to the accumulated deposition of fine-sized fuel ash onto the particles (agglomeration), maldistribution of air, fuel, and gases can occur, and the uniformity of the bed conditions is lost. If the upset is sufficiently large, the maldistributed region affects thermal performance of the system via reduced local heat transfer to the immersed heat-extracting surfaces in the bed. If agglomeration is not controlled, the inactive region can increase sufficiently so that performance deteriorates, and major areas of the bed are defluidized. In extreme cases, massive solidification of solids within the combustor can occur, resulting in premature shutdown and permanent damage to the combustor refractory, distributor surfaces, and in-bed tubes.

Although there are a number of factors affecting agglomeration, the properties of the coal ash are the most significant. Extensive work at the EERC (10) and Babcock and Wilcox (11) in the operation of the MDU 80-MW Heskett Station AFBC has shown that agglomeration under normal AFBC operating conditions can be expected for those coals with high levels of sodium and potassium in the ash. An example is testing performed with Beulah North Dakota lignite, which has from 6% to 12% sodium in the ash. During pilot-scale testing performed at the EERC and Babcock and Wilcox, and in the operation of the MDU 80-MW Heskett Station AFBC, agglomeration of the bed material was observed. The agglomeration appeared shortly after start-up of the system in all cases, and caused catastrophic shutdown after only 50 hours of operation in tests at the EERC, which used no bed drain and no fresh bed material makeup.

The detrimental performance of a system with agglomeration of bed solids can be reduced by several possible modifications to the system operating procedures, or to the fuel. Extra calcium-rich sorbent or "sodium-getter" additives could be fed to the system. The system could be operated in a low-agglomerating temperature regime or at higher bed material drain rates. The sodium content of the fuel could be reduced by ion exchange. Each modification exhibits economic limitations which must be considered when evaluating the effectiveness of the procedure. To determine the best option for minimizing the impact of agglomeration, the properties of each coal and the interaction of coal ash with sorbent and bed materials should be evaluated. High bed material drain rates and fresh bed material addition are currently being used at the Heskett Station to control agglomeration.

3.6 Summary

Coals are ranked by ASTM according to heating value and the volatiles and fixed-carbon contents. These differences mainly affect the thermal performance of the AFBC. Other properties, such as the ash level and chemical composition of the ash, are not rank-specific. The low-rank western coals are typically characterized as having a high volatile content, high moisture, high ash content, low sulfur, and high alkali content in the coal ash. The high-rank eastern coals are characterized by high heating values, high fixed carbon, low moisture, and high sulfur. There are many variances to these general trends, including variations within the same mine. These variances can have a major impact on the design and performance of the AFBC; therefore, actual coal properties, independent of rank, should be used to evaluate a specific application.

Although the properties of the fuel determine potential emissions of SO_2, particulates, CO, and hydrocarbons, these can all be controlled to acceptable limits by proper combustor design and operation. Even the emissions of NO_x and HCl, which are highly dependent on fuel properties, can be controlled with additional subsystems at extra cost. Thus the environmental performance for NO_x, HCl, and sometimes SO_2 are determined by the fuel-specific properties, while particulates, CO, hydrocarbons, and usually SO_2 are determined by system-controllable parameters. The thermal efficiency of AFBC systems is dependent on moisture, ash, sulfur, sodium, and fouling components in the coal.

The design fuel and any potential fuels that may be used in an AFBC system must be specified prior to the design of the system, as fuel properties have a significant impact on design and operation. These design-point conditions can be projections from pilot-scale tests, extrapolation from similar fuels or systems, or copies of existing successful systems. Care must then be taken to ensure that the system is designed to handle not only the typical properties of a particular coal supply, but also the extremes. With proper information, experienced designers and operators can exercise independent control of many parameters to achieve desired performance and costs, while taking into account fuel type and fuel properties.

4.0 COAL-WATER SLURRY

Testing has been performed at the EERC assessing the technical feasibility of burning low-rank coal-water fuels (CWF) in a fluidized-bed combustor. The objectives of the low-rank CWF testing were twofold. The first objective was the design and fabrication of a probe for the direct injection of slurry into the dense-bed zone of a bubbling FBC. The second objective was the actual combustion testing of a low-rank CWF in the 18" x 18" bubbling FBC at the EERC. The low-rank CWF used for the testing was prepared using the EERC's hydrothermal coal dewatering process, a process for the removal of liquid water from high-moisture coal by heating the coal under pressure in a water medium.

The bubbling-bed test furnace was modified to allow for the slurry feed. The skid-mounted feed system includes a progressive cavity pump which is gravity fed from the feed tank. A variable speed drive on the pump controls the CWF feed rate, which is measured by a Micromotion flowmeter with digital indicator. The CWF is generally agitated before introduction to the feed tank. An air-operated mixer is also provided in the feed tank to continuously mix the CWF during the test.

A CWF injection probe was designed and fabricated for this testing. The steel probe's simple design consisted of a straight, water-cooled stainless steel pipe. The major difference between this probe, designed for low-rank CWF, and those used by other investigators (12-14) for higher-rank coals is the absence of atomizing air, which inhibits the agglomerating tendencies of higher-rank CWFs. CFW was introduced into the FBC bed approximately 3 inches above the nozzle air distributor. Air was continuously supplied through the probe during start-up (before feed was initiated) to prevent any plugging of the probe by the bed material. This air was discontinued when CWF feed was started.

4.1 Test Description

The CWF used for these tests was produced from a Powder River Region subbituminous coal from the Absaloka Mine (Sarpy Creek field, Rosebud-McKay bed), which is located in the northeastern part of Bighorn County in Montana. This coal was chosen for CWF testing because as-received Sarpy Creek coal had been previously well characterized with the 18" x 18" FBC at the EERC.

The CWF combustion test matrix is presented in Table 3. The test series consisted of five separate test periods. A superficial gas velocity of 5 ft/sec and 20% excess air were specified for all tests in the matrix. Silica sand (No. 10) was used for bed material (static bed depth was maintained at 2.8 feet for all tests). Tests 1 through 3 were run at different bed temperatures, ranging from 1450° to 1650°F. Tests 4 and 5 were designed to compare the effectiveness of adding sorbent (limestone) mixed with the CWF versus adding dry limestone separately to the bed.

TABLE 3

CWF Combustion Test Matrix*

Test Number	Bed Temperature (°F)	Limestone Addition
1	1450	None
2	1550	None
3	1650	None
4	1550	Pulverized limestone mixed with the CWF
5	1550	Dry limestone (-8 x +20 mesh) added separately to the bed

* All tests were performed at 5-ft/sec gas velocity and 20% excess air. No. 10 silica sand was used as bed material. Static bed depth was maintained at 2.8 ft.

4.2 Coal-Water Fuel Properties

Approximately 10,000 pounds of Sarpy Creek CWF (60 wt% solids) were prepared using the hydrothermal dewatering process. The coal was processed at 625°F and then centrifuged to 65 to 70 wt% dry solids cake for storage. A coal-water/limestone fuel was prepared for Test 4 by adding pulverized limestone during the reslurrying process. This coal-water/limestone fuel was also mixed to produce a fuel that was 60% solids by weight. Dry limestone was crushed to -8 x +20 mesh for Test 5. The limestone was obtained from the Big Horn Limestone Company in Montana. Analyses of the coal-water and the coal-water/limestone fuels are presented in Table 4.

Both fuels showed stability up to eight hours, and have been stable up to five days in some cases. The fuel with added limestone was slightly more stable than the CWF without limestone. These fuels were prepared without any chemical additives to enhance flow behavior or stability. Therefore, any favorable flow behavior or stability of the fuels as compared to similar sized and quality as-mined coal were a result of the EERC hydrothermal dewatering process or the limestone addition.

4.3 Results and Discussion

After the slurry-feeding probe was designed and fabricated, the entire CWF feed system was tested during a short shakedown run. The following week the unit was restarted, and testing was performed according to the test matrix outlined in Table 3. A summary of the data from the five test periods is presented in Table 4. The data for each test period was collected and averaged during steady-state operation of the FBC unit.

Combustion efficiencies were determined for each test period using the input-output method. This method of calculation determines the amount of

TABLE 4

Average Test Conditions and Results

	Test No. 1	Test No. 2	Test No. 3	Test No. 4	Test No. 5
Bed Temperature (°F)	1450	1547	1654	1553	1550
Freeboard Temperature (°F)	1670	1734	1797	1788	1735
Gas Velocity (ft/sec)	5.0	5.1	5.1	5.0	5.1
Excess Air (%)	19.9	19.6	20.6	20.7	21.1
Static Bed Depth (ft)	2.8	2.8	2.8	2.8	2.8
Slurry Feed Rate (lb/hr)	146.1	140.5	135.8	147.6	141.2
Total A/S Mole Ratio	1.68	1.66	1.84	2.69	3.01
Sulfur Retention (%)	47.5	34.0	22.9	51.8	59.9
Total Alkali Utilization (%)	28.3	20.5	12.5	19.2	19.9
SO_2 Emissions (lb/MM Btu)	0.84	1.06	1.17	0.85	0.69
NO_x Emission (lb/MM Btu)	0.18	0.21	0.26	0.22	0.22
Combustion Efficiency (%)	99.4	99.7	99.7	97.4	99.3

uncombusted carbon in the fly ash as a fraction of the total carbon input with the fuel. Combustion efficiencies of the first three test periods (all without limestone addition) were very high, ranging from 99.4% to 99.7%. The efficiency appeared to increase slightly with increasing bed temperature. These values are equal to or somewhat higher than combustion efficiencies previously determined when testing Sarpy Creek as-received coal (as-received coal screw fed into combustor). More freeboard burning than normal was noted during the CWF testing, as evidenced by high freeboard temperatures. The freeboard temperature was generally between 140° and 230°F higher than the average bed temperature, with less temperature difference at the higher bed temperatures. The freeboard burning is probably not a significant problem, but will shift additional heat transfer into the convective passes of an actual boiler. For previous testing with as-received coal (-1/4 in.) screw fed into the bed, freeboard temperatures were generally less than 100°F higher than the average bed temperature.

Combustion efficiencies, although determined for tests with limestone addition (Tests 4 and 5), should not be compared to the tests without limestone addition. Uncalcined limestone ($CaCO_3$) can add significant quantities of CO_2 to the uncombusted carbon in the fly ash, thereby "artificially" lowering the combustion efficiency.

Carbon monoxide (CO) emissions were low during the CWF testing, generally less than 200 ppm. Some small intermittent CO spikes were seen throughout the testing. The low CO levels at excess air levels of approximately 20% were another indication of good fluidization and combustion stability.

Emissions of NO_x were very low when burning the CWFs, ranging from 0.18 lb/MM Btu at 1450°F to 0.26 lb/MM Btu at 1650°F. These emissions are significantly lower than those when burning the same coal as-received into the FBC, which resulted in NO_x emissions ranging from 0.24 to 0.58 lb/MM Btu. The emissions of NO_x when burning the CWF are well below limits set by the 1979 New Source Performance Standards (NSPS) of 0.6 lb/MM Btu.

In Tests 1 through 3, the emissions of SO_2 were investigated when burning CWF at various bed temperatures. Additional sorbent was not used during these three tests in order to quantify the sulfur capturing capacity of Sarpy Creek's alkaline ash. Sulfur retention was highest at 1450°F (47.5%) and decreased as bed temperature was increased, dropping to 22.9% retention at 1650°F. These results are not significantly different than those observed previously when testing as-received Sarpy Creek coal. In the previous testing, the maximum sulfur retention also occurred at 1450°F.

To meet NSPS, additional sulfur capture is required when burning Sarpy Creek coal. Therefore, Tests 4 and 5 were included to compare the efficiencies of two different methods of adding limestone to the bed. In Test 4, pulverized limestone was added directly to the CWF during the slurrying process. Pumping this coal-water/limestone fuel into the bed resulted in a very simple feed system for both the coal and limestone. In Test 5, dry limestone (-8 x +20 mesh) was added to the bed pneumatically, separate from the CWF. A higher retention was observed for the separately injected limestone (59.9%) than for the limestone mixed with the slurry (51.8%). This difference is due to the fact that more limestone was added in Test 5 (dry limestone feed) than Test 4 (limestone mixed in slurry). The total molar alkali-to-sulfur ratio (A/S) for Test 5 was 3.01, which is somewhat greater than 2.69 for Test 4. The total A/S takes into account the calcium and sodium contributed by both the inherent coal ash and the added limestone. To compare the sulfur capture in Tests 4 and 5 on an equal basis, it is necessary to look at the alkali utilization rather than simple sulfur retention. Alkali utilization is calculated by dividing the sulfur retention by the alkali-to-sulfur ratio. Alkali utilization, like sulfur retention, increases with decreasing bed temperature over the range of temperatures studied. The form of calcium (there was no detectable sodium in the limestone and only very little in the coal ash) or the method by which it was added had little effect on its utilization. All three tests run at the same bed temperature (1550°F), which included the two methods of limestone addition and a test without limestone addition, had essentially identical alkali utilizations: 19.2%, 19.9%, and 20.5%.

Samples of bed material drained from the FBC after each test period were submitted for elemental and size analysis. From the sieve analysis, little particle growth was evident. Visual observation of the bed-material particles and elemental analysis indicated very little ash deposited on the surface of these particles. The fine ash was elutriated from the bed before it was able to react with the silica sand bed material. Since ash does not collect in the bed, it is probable that a continuous bed removal system will not be required when burning CWFs of the coal.

4.4 Summary

A low-rank CWF prepared from a Powder River Region subbituminous coal using the EERC's hydrothermal coal dewatering process was successfully burned in a 18" x 18" atmospheric bubbling FBC. The 60-wt% dry solids CWF was pumped directly into the dense-bed zone through a simple, water-cooled pipe without the aid of a nozzle or atomizing air. Significant results from the testing include:

- The CWF exhibited flow behavior that was acceptable for short-term handling and ease of feeding. In addition, there was no detrimental rheological effect to hydrothermally treated low-rank CWF from the addition of limestone for sulfur capture.

- Limestone utilization for the reduction of SO_2 emissions was equal for pulverized limestone added directly to the CWF versus dry limestone added separately to the bed (-8 x +20 mesh). The utilization appeared significantly dependent on bed temperatures.

- Combustion efficiency as measured by carbon burnout was very high, ranging from 99.4% to 99.7%. These efficiencies are equal to or slightly greater than efficiencies previously obtained for the as-received Sarpy Creek coal when screw fed into the same FBC.

- Emissions of NO_x when burning CWF were significantly lower than previously seen when burning the same coal as-received. Emissions ranged from 0.18 to 0.26 lb/MM Btu, increasing slightly with increasing bed temperature.

- Little growth in bed particle size or increase bed weight was noted during the CWF testing. Therefore, a continuous spent-bed removal system may not be required when burning CWFs produced from similar coals.

5.0 CORROSION, EROSION, AND DEPOSITION OF FBC BOILER TUBES

Systematic studies were performed at the EERC investigating the effects of coal properties on corrosion, erosion, and deposition of fluidized-bed combustion heat-transfer surfaces. Seven coals were tested covering a range of ash properties and coal rank. The test coals included two Texas and one North Dakota lignite, a Montana and a New Mexico subbituminous coal, and an Illinois and a Kentucky bituminous coal. The 1000-hour tests were performed using an 8" x 8" bubbling fluidized bed operated at a velocity of 7.5 ft/sec, an average bed temperature of 1550°F, and an excess air level between 20% and 30%. Limestone was used as the bed material and was fed at a rate to achieve NSPS for the coals tested.

The goal of this work was to identify differences and similarities in materials performance between the different tests. Individual measurements for each metallographic feature were taken. Results presented in this summary are generally averages for different categories. Data anomalies are averaged out, and an overall picture of how metal loss was affected by the various parameters under study is presented. Therefore, this summary is meant to present the relative trends observed. Absolute numbers for metal loss, sulfide penetration, deposit/scale formation, and other metallographic features at full scale will vary from unit to unit, depending on geometry, operating conditions, and other factors. With this qualification, the general trends observed are shown in Table 5 and listed below:

- Coal type, metal type, and surface temperature all had a statistically significant effect on the amount of metal loss. As determined by diameter-loss measurements, the following trends were observed:

  - The ranking of metal loss as a function of coal type, from highest to lowest, was Pyro, South Hallsville, Gibbons Creek, Beulah, River King, Sarpy Creek, and Navajo. Average metal loss ranged from 122 microns across the diameter for the Pyro test to 41 microns for the Navajo. This would relate to 61 and 20 microns for each wall, respectively.

  - Metal loss was 5 times as great for the carbon steel as compared to the 304-, 316-, and 347-stainless steels. The 347-stainless steel was the best performer of the stainless steels tested.

  - Metal loss decreased with increasing temperature for the in-bed tubes and increased with increasing temperature for the convective pass tubes.

  - No statistical differences in metal loss were observed between the in-bed, splash zone, and convective pass tubes.

  - The amount of metal loss increased with an increase in the calcium and limestone feed rates, but decreased with an increase in the sulfur and sodium feed rates. Bed chemistry parameters causing a higher metal loss included the S/Ca ratio and the CaO content in the bed. Bed chemistry parameters causing less metal loss as they increased were the mean bed particle size, the sodium and potassium concentrations, the SO_3 concentration, the SiO_2 and Al_2O_3 weight ratios, and the base-to-acid ratio.

  - Measurements of metal loss determined across the diameter of the tube differed from those taken across the tube wall for some cases. The diameter loss measurements are believed to be more accurate, as they were a direct before-and-after measurement at the same location, where wall loss measurements were not.

- Coal type, metal type, surface temperature, and location all had statistically significant effects on the amount of sulfide penetration resulting from the 1000-hour exposure. The following trends were observed:

  - The greatest amount of sulfide penetration was observed for the test using Pyro coal, followed by Beulah, Gibbons Creek, Sarpy Creek, South Hallsville, Navajo, and River King. Pyro, the worst case, had an average sulfide penetration of 52 microns, while the sulfide penetration of the River King test averaged 12 microns.

TABLE 5

Summary of Test Data from 1000-Hour Tests

	Average Measurements for all Tubes in Category, microns				
	Diameter Loss	Wall Loss	Sulfide Penetration	Deposit/ Scale	Pit Depth
<u>Coal Type</u>					
Beulah	70	82	47	502	117
Gibbons Creek	74	161	31	65	105
Navajo	41	116	18	19	59
Pyro	122	185	52	188	174
River King	70	285	12	43	82
Sarpy Creek	54	233	32	30	86
South Hallsville	84	50	31	20	115
<u>Metal Type</u>					
304 SS	70	133	44	104	114
316 SS	50	69	27	96	77
347 SS	4	154	24	82	28
Carbon Steel	234	372	28	285	262
<u>Location</u>					
In-Bed	62	163	37	163	99
Splash Zone	77	135	55	91	132
Convective Pass	86	164	15	88	101
<u>Surface Temperature, °F</u>					
400	142	237	25	317	167
1100	56	127	43	104	99
1550	-11	127	54	50	43
250	23	96	10	42	33
700	47	133	18	115	65
1200	196	270	15	105	211

- Sulfide penetration was the greatest for the 304-stainless steel tubes, and was similar for the 316-stainless, 347-stainless, and carbon steels.

- The depth of sulfide penetration increased with increasing metal surface temperature.

- Sulfide penetration was greatest in the splash zone, followed by the in-bed tubes, with the least amount of penetration occurring in the convective pass tubes.

- An increased sulfur feed rate caused deeper sulfide penetration and thicker deposits on tubes. As the mean bed particle size decreased, sulfide penetration increased.

- Coal type, metal type, and surface temperature had statistically significant effects on the amount of deposit/scale buildup on the heat-transfer tubes. The following trends were observed:

  - The largest amount of scale/deposit was observed with the Beulah lignite. In this case, deposits as thick as ½ inch were observed. Deposit/scale thickness from the other tests ranged from 19 to 188 microns. Deposit/scale thickness increased in the following order: Navajo, South Hallsville, Sarpy Creek, River King, Gibbons Creek, Pyro, and Beulah.

  - The carbon steel tubes had almost three times as much buildup as the stainless steel tubes. Little difference was noted between the stainless steels.

  - Deposit/scale was much greater for the in-bed tubes than for the splash zone and convective pass.

  - Analysis of the deposit/scale showed that the majority of the matrix was calcium sulphate- or sodium sulfate-based.

  - The deposit/scale thickness increased with increases in the sulfur and sodium feed rates and decreased with increases in the limestone feed rate and average bed particle size.

  - The heat-transfer coefficient was significantly reduced, up to 40% in the worst case, as a result of the deposit/scale buildup on the tube surfaces.

  - Similar deposit/scale buildup was noted at the MDU 80-MW Heskett Station and the NSP 130-MW Black Dog Station when firing coals similar to those used in the EERC tests.

- Of the materials tested, 347-stainless steel showed the best overall performance, followed by the 304- and 316-stainless steels. The carbon steel tubes, in most cases, exhibited performance that would be unacceptable to a boiler operator.

- Several coal-related properties affect metal performance. Some of these are measured directly, while others, such as the composition of bed material, are measured indirectly. Trends were as follows:

  - As the sulfur feed rate increased, so did metal loss, sulfide penetration, and the amount of deposition.

  - Increasing amounts of calcium fed with the coal (not including that contributed by the limestone) tended to increase metal loss and sulfide penetration.

- The deposit/scale thickness and sulfide penetration increased with an increasing sodium feed rate.

- Higher limestone feed rates tended to reduce metal loss, sulfide penetration, and deposit/scale thickness.

- Tests with smaller bed particle size exhibited more metal loss, sulfide penetration, and deposition than tests with larger bed particle size.

- An increase in the silica-to-alumina and base-to-acid ratios decreased metal loss.

It is hoped that this information will help designers and users of bubbling fluidized beds to evaluate the impact of coal properties, metal type, metal surface temperature, and location of the corrosion, erosion, and deposition on tubes in the FBC. This data should be used carefully, as this summary was based on average values for different categories. As in most cases, there may be exceptions for different cases, and results should be examined on a tube-by-tube basis if trying to match a specific application. It should be remembered that other factors, including tube bundle geometry and operating conditions, also influence the level of corrosion and erosion and must be taken into consideration when evaluating potential wear. Details of this work are presented in the EERC topical report entitled "Corrosion, Erosion, and Deposition of AFBC Boiler Tube Surfaces."

6.0 ADVANCED CONCEPTS: COAL PRETREATMENT CELL

The coal pretreatment cell was developed as a new process for an advanced FBC system. The impetus of the original program was to develop a new system or improve existing equipment to realize a reduction in overall capital and operating costs, increase boiler and overall efficiency, and/or reduce emission levels.

A multiphasic approach was taken to accomplish the goals of this task. Initially, a systematic listing of identifiable problems in current FBC technology was developed. A second step involved breaking down the FBC process into individual processes, such as calcination, sulfation, drying, devolatilization, carbon burnout, etc. Conditions needed to optimize each of these processes, independent of the rest of the process, were determined, based on EERC experience, FBC theory, and published results.

Using the list of problems and the individual process constraints developed in the first two steps, new concepts that could be incorporated into a design to solve a particular problem or improve performance of a certain subsystem were formulated. These ideas were qualitatively screened and refined based on technical, environmental, and economic criteria.

Based on these preliminary efforts, the EERC focused attention on developing a pretreatment cell to be used in conjunction with any number of FBC designs. The operation and function of the pretreatment cell, as developed, begins with raw coal being fed into the pretreatment cell. In the pretreatment cell, moisture will be driven off, some devolatilization will occur, and the coal will be fragmented into smaller pieces. The extent and severity of these processes can be controlled by varying several operating parameters. Air-to-fuel ratio and residence time are the primary control variables. The reactions and changes will occur using heat generated from combusting a small portion of the coal, so no external heat source will be required.

The pretreatment cell will be operated as a fluid bed. Velocity and vessel design are chosen to allow classification of the fuel. Existing data show that an optimal size exists for fuel fed into an FBC, in terms of both top and bottom size. As a result, coal sizing is often a significant operating cost. Large-sized coal (top size determined by testing) will be fed into the pretreatment cell. The vessel is designed with less cross-sectional area on the bottom (high velocity) than at the top of the bed surface (lower velocity) so that the entire bed will be fluidized even when feeding large coal particles. Smaller chunks of coal will be removed from the top of the bed to be fed into the combustor. The larger chunks will remain in the lower level of the bed until they become reduced in size due to drying, volatilization, and the action of the bed. This action will allow the use of coal with a larger top size, thereby reducing coal preparation costs.

In most combustor designs, excessive fines cause reduced combustion efficiency due to elutriation. In the pretreatment cell, velocities will be maintained at a sufficient level to remove fines below 200 mesh. These fines will be removed from the top of the pretreatment cell with the moisture and volatiles and will become a part of a low-Btu gas stream that can be burned using conventional burners, as will be discussed later. Therefore, only a minimal amount of fines will be fed into the combustor, and carbon burnout should increase.

Moisture and some volatiles will be driven off in the pretreatment cell. This will be done at a very low air-to-fuel ratio, using only heat from the coal. The gas stream from this process, combined with the coal fines, will make up a low-Btu gas that can be used somewhere else in the system, such as in the freeboard or convective pass of the combustor. Pretreatment can have several applications, but maintaining steam quality during turndown may have the greatest potential benefit. Coal pretreatment can not only smooth out the steps when load is controlled by removing segments of bed, but should also increase the range of turndown.

Removal of the moisture and volatiles in the pretreatment cell will also act as an "equalizer" for the fuel being fed into the main combustor. All fuel burned in the combustor will be similar in terms of moisture and volatiles and should vary only in the ash. This feature should increase the overall fuel flexibility of the unit.

Mass and energy balances have been performed using this concept. A comparison was made using a conceptual 200-MW bubbling FBC with and without a pretreatment cell. Data for the FBC under normal operation was taken from a previous EPRI study (15). For the case using the pretreatment cell, data taken from previous work (16,17) was used to generate material and energy balances around the pretreatment cell. For the combustor, velocities and excess air levels the same as the base-case FBC were used. This analysis showed a reduction of 17% in the overall plan area, even with the pretreatment cell included. This will be accompanied by a significant reduction in height for the pretreatment cell versus the height of the fluid bed it replaces. This should result in substantial reductions in capital costs.

Mass and energy balance calculations also indicate an optimal total air-to-fuel ratio of 1.105. This calculation was done assuming an air-to-fuel ratio of 1.20 for all combustion processes and is compared to a total air-to-fuel ratio of 1.20 for the base-case FBC. The resulting lower air-to-fuel ratio indicates higher overall boiler efficiency and should result in lower capital costs because of reduced fan requirements. Figure 1 shows a conceptual drawing (relatively to scale) on how the pretreatment cell would be incorporated into a CFBC.

To summarize, the proposed advanced concept should have many advantages over conventional fluid-bed combustion, including the following:

- Minimal coal preparation will be required. Both fines and large coal particles will be efficiently handled.
- The pretreatment cell will be smaller, requiring fewer feed points and less plan area than the equivalent amount of combustor that it replaces. The total height requirement for the pretreatment cell will also be less than that of the combustor it replaces.
- Fuel flexibility will increase by "equalizing" the fuel (in terms of moisture and volatiles) that is being fed into the combustor.
- The total plan area of the pretreatment bed and the combustor will be approximately 17% less than for an equivalently sized conventional FBC.
- Turndown will be improved by maintaining steam quality at low load conditions.
- Higher volumetric heat-release rates are expected.
- Tighter constraints on coal size, both top and bottom size, will result in higher combustion efficiency and higher heat removal in the fluid bed.
- Staging of air and lower total air usage should result in lower NO_x emissions.
- Separate burning of the volatiles and char may result in lower N_2O emissions.
- Start-up may be accomplished without the use of an auxiliary burner.
- The pretreatment cell may be retrofittable to existing units, with similar benefits realized.
- The pretreatment cell will be small enough to allow for modular construction.

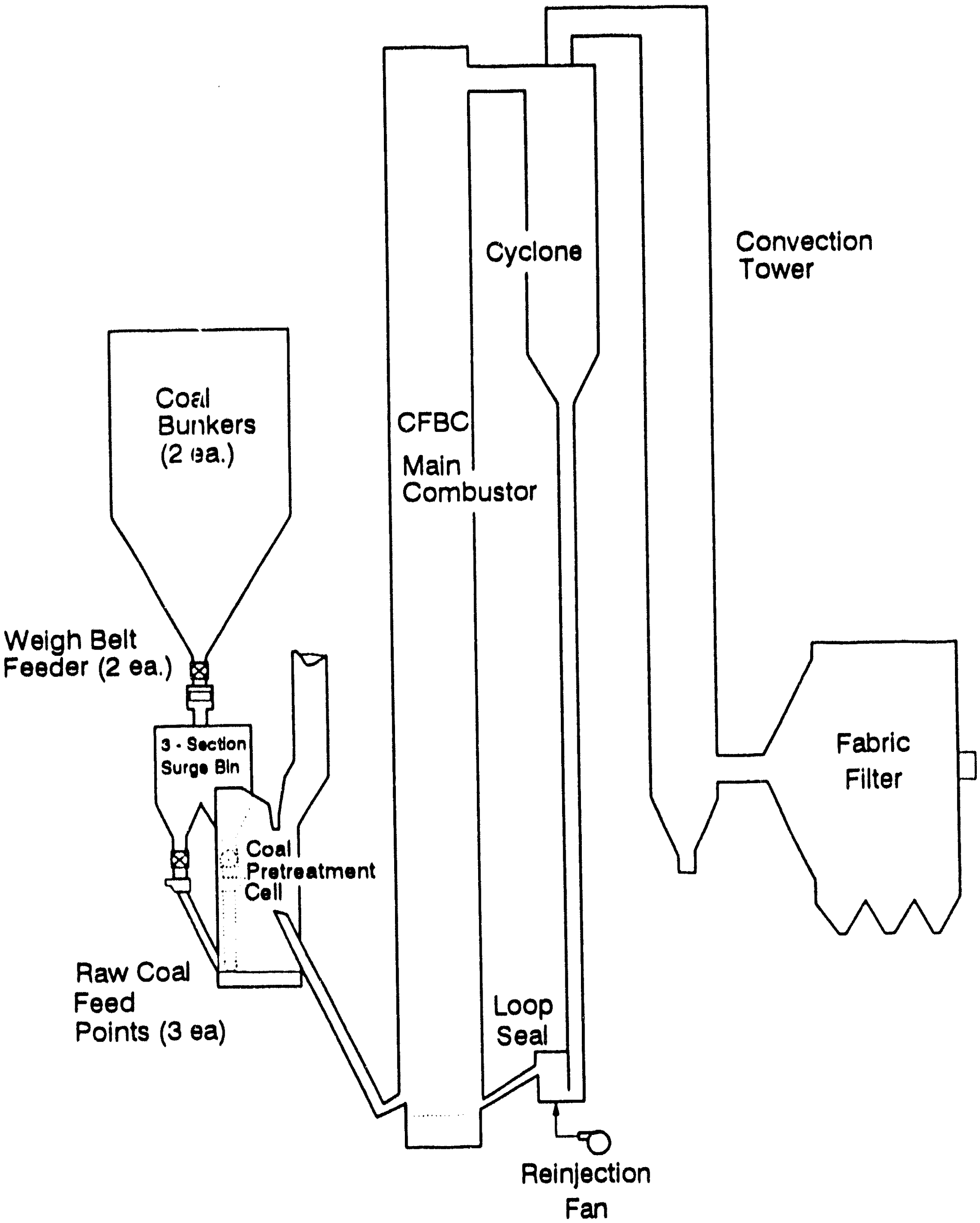

Figure 1. Coal pretreatment cell with CFBC (100-MW capacity).

7.0 SYSTEM SIMPLIFICATION

As more and more boilers utilize fluidized-bed combustion systems because of their efficiency, fuel flexibility, and low emissions capability, it becomes increasingly important to understand the control philosophy required to optimize these features. A FBC consists of a large number of interrelated variables which must be carefully controlled for optimum performance. The level of control is dictated by the type of FBC system, the application of the system, and the availability of trained personnel to operate the system. A study was completed that evaluated existing control systems and needs and proposed alternatives for improved control. Results are summarized below.

Market potential for the use of AFBC technology in the commercial and industrial sectors is great; however, to increase the acceptability of this technology, low cost, reliability, and ease of operation must be inherent to the system. This can be accomplished, in part, by the development of a good control system. The control system must be developed to the point where the boiler will be controlled within desired operational parameters without the availability of highly trained operators. One method of accomplishing this is to establish expert systems that will become the "trained experts" to perform the bulk of control activities, thereby allowing the owners of small boilers to operate with minimal personnel. Optimizing the control of the operating parameters should make the FBC easier to operate, reducing operating costs while increasing system reliability.

An expert system is a knowledge-based computer system that can mimic the human thought process. The computer is able to reason according to a set of predefined rules to solve a problem that would otherwise require an expert or significant expertise to solve. Expert systems can capture a lifetime of individual expertise and make that expertise available to practitioners who lack comparable abilities for solving problems in the field. An expert system augments a process control system by evaluating the data and drawing conclusions. The common goal of all expert systems is to tap the ability of the computer to store large amounts of technical know-how, to access this data when needed, and to make intelligent judgments about likely causes of failure or poor performance.

The function of control systems is to compare desired values (set points) and actual values (output variables) to adjust the amount of fuel, air, and water (manipulated variables) to make the output variables match the set points. A skillful operator manipulates the control variables to optimize the boiler performance, rather than simply making the system run. An expert control system would be expected to do the same.

A number of different and sometimes conflicting factors go into the control philosophy of a plant. Some of these factors are operating objectives, economic operating conditions, regulatory requirements, and physical process constraints. Specific priorities must be established, such as the choice between maximum efficiency and maximum reliability and the choice between equipment protection or continuity of operation.

Many operations may be controlled automatically, rather than manually, for several reasons. A degree of automation keeps operator work load at manageable levels; if an operator is relieved of routine tasks, he can concentrate on optimizing plant performance, with a corresponding increase in plant efficiency. Limiting the number or complexity of operator functions will reduce the possibility for human error and, thereby, decrease equipment damage. Adding automatic functions can reduce the amount of time required for start-up and shutdown. Increased automation does require additional capital cost for computers, controllers, software, and instrumentation, so the desired level of automation must be carefully considered.

The most effective boiler control system is one which is stable and responsive; that is, the controlled variables remain close to their set point values without cycling and recover quickly from system disturbances without excessive overshoot or oscillation.

As power plants become more complex, improved control systems, state-of-the-art diagnostics, and expert systems will become essential. Technology has progressed to the point where we can make available, quickly and accurately, knowledge that only existed before in the minds of a few scattered "experts."

8.0 AGGLOMERATION AND DEPOSITION

Although FBCs typically operate at low temperatures (1450° to 1700°F), evidence from pilot, industrial, and utility boilers indicates that certain ash components have the potential to cause ash-related problems. These problems can manifest themselves as agglomeration and sintering of the bed material, or as deposition on the heat-exchanger tube surfaces. The EERC performed bench- and pilot-scale tests, in addition to sampling from full-scale units, to uncover the underlying mechanisms of agglomeration and deposition. Results from this work are summarized below.

8.1 Agglomeration

Under steady-state conditions, reaction between various ash species and the bed particles occurs. At the initial stages, ash species deposit on the surface of the particles. The process has been observed for both quartz and limestone particles. The species that deposit tend to be sulfate-rich, indicating that the overall process at this stage is that of sulfate-to-sulfate sintering. At this stage, limited evidence of localized melting exists. The process continues, resulting in the formation of a thick ash shell (about 10% of the particle diameter). The next stage can be seen as the onset of agglomeration. This occurs when two or more ash-coated bed particles cohere to form a larger particle. The cohesion is via the sulfate-rich ash coating due to sulfate-to-sulfate sintering. If the cohesion continues, the next stage will occur, which is the most serious, and may result in the formation of large agglomerates and the eventual slumping of the bed.

A fluidized bed is capable of tolerating a fraction of bed particles in the oversized range; however, once the oversized particles exceed a critical value, the degree of mixing will be reduced. With poor mixing, localized high temperatures are reached for relatively extended periods of time. This leads to the melting of ash species and, in some cases, the bed material. The cohesion under these condition is via a silicate matrix. This matrix results in accelerated cohesion, reaction, formation of a more liquid phase, and growth of agglomerates, compared to the sulfate sintering that occurs at the earlier stages.

The critical stages of agglomeration can be summarized as follows:

1. Initial deposition/condensation of volatile alkaline ash species and fine-grained calcium on the surfaces of bed particles.

2. Sulfation of the alkalies to form alkali sulfates. This may occur before, during, and/or after deposition.

3. Adhesion and cohesion of additional ash species on the initial ash layer.

4. Cohesion of two or more particles to form an agglomerate via sulfate sintering.

5. The formation of a large agglomerate.

6. The fraction of oversized particles exceeding the critical value for the fluidizing conditions.

7. The formation of high-temperature zones within the bed due to poor fluidization.

8. The high temperature causing ash melting and the formation of a molten silicate melting.

The initial stages have been shown by detailed surface science and scanning electron microscopy to be due to sulfate formation at the surface of the bed particle (1,18-22). The importance of sulfate in the agglomeration process was shown by Bobman (2,23) during experiments with a 2" fluidized-bed reactor. It was shown that agglomeration of fly ash particles with quartz and limestone beds only occurred when SO_2 was added to the fluidizing air. Furthermore, the tests had to be conducted for relatively long periods, at least 48 hours, before significant agglomeration occurred. This further confirmed that the agglomeration was occurring due to the sulfate sintering mechanism, as liquid-phase sintering associated with an aluminosilicate melt would be expected to be rapid.

The importance of the form of sodium in the coal is evident when comparing results from tests with a North Dakota lignite, a Texas lignite, and an Illinois #6 bituminous. Although the coals had sodium plus potassium levels of 9.1%, 7.2%, and 3.4%, respectively, agglomeration was only noted for the case with the North Dakota lignite where the sodium occurred in a form that allowed volatilization during combustion (1).

8.2 Deposition on Tube Surfaces

Sodium, potassium, calcium, and sulfur can play a similar role in deposition on in-bed and convective heat-transfer surfaces in the fluid bed. Evidence accumulated by the EERC (24,25) and other researchers (26-28) indicates that tube deposits are the result of a combination of fine-grained deposit-forming particles arriving at the tube surface followed by sticking/bonding of those particles onto the surface. Condensation of alkaline salts from the vapor phase occurs in the temperature range of 1000° to 1475°F. At the same time as these alkali salts are condensing and forming sticky surfaces, fine-grained ash particles (<1 micron) are arriving at the tube surface. These fine-grained particles are predominantly calcium oxides and sulfates. These particles then become bonded to the tube surface via a sintering process. Sintering of the deposits continues after initial deposition, forming deposits with a dense matrix. Other ash species can then be trapped within this captive surface, as noted by inclusion of iron oxide and other ash constituents in analyzed deposits.

Based on the proposed mechanism and on results from pilot- and full-scale testing, the importance of the elemental and mineralogical composition of coal mineral matter becomes obvious. Coals with organically bound alkalies cause more deposition than those with no alkali or clay-associated alkalies. The presence of certain aluminosilicates within the ash matrix may fix these alkali elements within a viscous melt phase, thereby nullifying their deposit-forming potential.

A series of pilot-scale tests were performed by the EERC to study the impact of coal type on deposition, erosion, and corrosion. Seven 1000-hour tests were performed utilizing a Beulah North Dakota lignite, a Sarpy Creek Montana subbituminous coal, a Navajo New Mexico subbituminous coal, Gibbons Creek and South Hallsville Texas lignites, a River King Illinois #6 bituminous coal, and a Pyro Kentucky #9 bituminous coal. These coals represent a wide range of coal and ash properties (properties given in Reference 29). Coal ash properties significantly affect the amount of tube deposition. The amount of deposition is also controlled by metal type, temperature, and tube location, as illustrated in Table 6. This deposition has an adverse affect on heat transfer, with heat-transfer coefficients decreasing by over 40% during the course of a run for the worst cases.

An analysis of variance indicated that a higher sulfur content in the coal causes thicker deposits on the tubes. Deposit thickness was found to increase significantly as the amount of sodium fed into the unit increased. There was no correlation, however, between the amount of sodium and potassium in the bed and the deposit thickness. The total amount of calcium added to the coal had no impact on deposit thickness, but the thickness showed an increase with calcium when only the organic portion was considered. Total deposit thickness decreased with an increase in limestone feed rate. It should be noted that the elemental contents in the coal were compared on a lb/MM Btu basis, not as weight percent in the coal.

These results substantiate the proposed mechanism. Coals with higher concentrations of volatile alkalies showed higher deposition rates. The presence of calcium was critical in the deposit formation, but all forms of calcium present in the coal did not result in major depositional problems. As in the case of the agglomeration work, coals that produced more SO_2 showed a higher propensity to form a sulfate-based matrix, which is the basis for initiating the deposit. Analysis of the deposits showed the major phase in the deposit was a calcium/sodium sulfate material. Although limestone addition increases the total amount of calcium in the bed, the resultant

TABLE 6

Comparative Statistics on Deposit/Scale Thickness[a]

	Number of Observations	Lowest Value	Highest Value	Mean	Standard Deviation
Temperature, °F					
250	20	0	210	42	66
400	31	0	1560	317	473
700	20	0	580	115	193
1100	54	0	720	104	190
1200	23	0	600	105	182
Coal Type					
Beulah	29	120	1560	502	349
Gibbons Creek	29	10	520	65	128
Navajo	27	0	150	19	34
Pyro	17	10	1240	188	385
River King	24	0	370	43	73
Sarpy Creek	23	3	150	30	31
South Hallsville	26	0	50	20	14
Metal Type					
304 SS	48	0	1100	104	215
316 SS	49	0	720	96	179
347 SS	47	0	910	82	175
Carbon Steel	31	0	1560	285	433
Location					
In-Bed	92	0	1560	163	319
Splash Zone	63	0	600	91	160
Convective Pass	20	0	650	88	177

[a] The minimum and maximum values from each tube were used in the statistical analysis. All units are microns.

calcium sulfate is in the form of larger limestone-based particles and does not appear to impact the overall deposition process. In fact, the decrease in deposition noted with increased limestone addition may be due to dilution. Similar results have been reported by other researchers (26-28).

8.3 Incidents in Full-Scale Systems

Both agglomerates and in-bed tube deposits from full-scale boilers have been recovered and studied at the EERC. The following description of these materials provides additional evidence in support of the previous discussion. This analysis also shows the importance of using advanced analytical techniques for analyzing these deposits and elucidating whether the noted problem is due totally to ash chemistry, or in combination with a system upset.

The 80-MW bubbling FBC at the MDU Heskett Station has experienced deposition on both in-bed and convective pass heat-transfer surfaces, causing significant reduction in overall heat transfer. The superheat steam temperature decreased by 40°F over a four-month period due to deposition on the in-bed superheat tubes. The unit is fired with Beulah lignite and has a bed material of river sand. Deposits from this unit were collected and analyzed using x-ray fluorescence, x-ray diffraction (XRD), electron probe microanalysis (EPMA), and scanning electron microscopy point count (SEMPC). The focus of the analysis was to establish the mechanism of deposit formation and growth. Detailed results are published elsewhere (24).

Analytical results show that the Beulah coal ash has a definite prcpensity for deposition. The formation of an ash coating on bed material is a precursor to agglomeration. The ash coating is derived from the coal, in particular, the calcium, sulfur, and sodium. The deposits, including the ash coating, possess chemical compositions very different from the spent-bed material, indicating that the deposition mechanism is a selective process. All deposits are predominantly enriched in calcium and sulfur. Significant iron enrichment was observed in the convective pass deposit; however, it did not appear responsible for the deposit growth.

The evidence suggests that deposit growth is due to the formation and presence of sodium calcium sulfate in the bed. This material is formed from the organically bound sodium and calcium in the Beulah coal reacting with sulfur. There was no free calcium observed in the deposits. Sulfate species tend to sinter. The matrix was too fine-grained to establish the presence of a melt phase. It should be noted that molten sulfate systems tend to crystallize rapidly upon cooling. The mode of growth may be a molten sulfate phase. Certainly the presence of sodium with the calcium would be expected to lower the melting point. The presence of nepheline, anorthite, and gehlenite suggests relatively high-transient temperatures within the bed. The silicate phases, while exhibiting melting behavior, were not present in significant quantities to have a significant effect on deposition phenomena.

8.4 Agglomeration in Full-Scale Utilities Due to Operational Upsets

The cases and mechanisms of agglomeration and deposition discussed so far are the result of coal ash chemistry under normal operating conditions in the FBC. However, agglomeration can also occur due to maldistribution of air, temperature upset, or other operational difficulties. The cause of agglomeration can be determined by using advanced analytical techniques to examine the raw coal, the original and spent-bed material, and any agglomerates that form. The following example presents results from a study done at the EERC on an agglomerate formed in the 130-MW bubbling FBC at the NSP Black Dog Station.

The agglomerate was supplied by NSP personnel after excessive agglomeration was observed during a shakedown test with Sarpy Creek, a Powder River subbituminous coal, and an inert-bed material of fired clay. The agglomerate was dense and consisted of two distinct regions, classified as sintered and slag-like. The two regions and the virgin bed material were analyzed using SRD, EPMA, and SEMPC. The focus of the analysis was to elucidate the reason for the agglomerate formation: specifically, was it related to ash chemistry or operating conditions?

The data indicated that the sintered deposit was due to the melting of the ash species which acted as the adhesive between the kaolinite particles. There was relatively little interaction between the ash matrix and the kaolinite-bed material, as shown by the fact that there were limited amounts of kaolinite-derived particles in the sintered deposit. The data contrasts markedly with that of the slag samples. The low quantity of pure kaolinite and kaolinite-derived particles and the presence of crystalline mullite indicates that extensive melting and recrystallization from the melt took place. In order for this to occur, temperatures in excess of 2400°F are required. This indicates that excessive temperatures were reached in the combustor which were directly responsible for the agglomeration. There was no evidence to suggest that the agglomeration was due to the reaction of alkaline ash components to form a sticky matrix at the average operating temperature of 1750°F.

8.5 Summary

Advances in analytical techniques for examining coal minerals, fly ashes, and deposits have improved the understanding of agglomeration and tube deposition in FBC systems. Both of these phenomena appear to be initiated by the same basic mechanism and are directly related to the amount and distribution of sodium, potassium, calcium, and sulfur in the feedstock.

Agglomerates and deposits are initiated and formed by the same general mechanism. Organically bound-alkali species are volatilized during coal combustion and condense on bed-material surfaces or on in-bed tubes. The condensation mechanism involves gas-to-solid condensation, either in the combustion gases forming partially fused or solid crystals. These can subsequently adhere to cooled surfaces in the combustor. Condensation can also occur directly by nucleation and growth on the substrate.

Alkali species can form sulfates, either in the gas phase or immediately upon condensation. These alkali sulfates sinter over a period of time, forming a very tenacious fine-grained, dense layer. In the case of agglomeration, two or more particles can stick together to form an agglomerate via this sulfate sintering, eventually causing defluidization. Tube deposition will impair heat transfer and reduce boiler load.

Knowledge of the total alkali in a fuel is not sufficient to predict the potential for agglomeration or deposition. The alkali must be in a form that will allow it to be volatilized during combustion, i.e., organically bound. Those alkalies associated with clay minerals are generally not available to participate in deposition or agglomeration. Other minerals associated with the fuel are also important. Aluminosilicate phases can compete for the released alkali and form higher melting point clays, rendering the alkalies inert in terms of agglomerate and deposit formation. Therefore, it is imperative to know the mineralogical composition of a fuel, as well as its chemical composition.

Advanced analytical techniques, especially SEMPC, are important in forensic studies of problems encountered in operating systems. The use of this technique can help determine whether agglomeration problems are due to ash chemistry or to combustor-operating conditions. This distinction is important, as the method of mitigation will be different for the two instances. With proper understanding of the fuel and its potential for agglomeration and deposition, even potentially problem fuels such as Beulah North Dakota lignite, with 8% to 12% of its ash present as organically bound sodium, can be successfully burned in utility-scale plants, as evidenced by the highly successful operation of the 80-MW Heskett Station. Information gathered from this type of analysis has also been used by the operators of the NSP Black Dog Station to modify start-up and fluidizing procedures, to virtually eliminate their agglomeration problem.

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