3.6 Coal Science

COAL SCIENCE

Annual Technical Progress Report
for the period July 1, 1989 through June 30, 1990

Including

the Quarterly Technical Progress Report
for the period April through June 1990

by

Joseph H. Hartman, Project Manager
University of North Dakota Energy and Environmental Research Center
Box 8213, University Station
Grand Forks, North Dakota 58202

August 1990

Contracting Officer's Representative: ˽eroy Dockter

for

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

Work Performed Under Cooperative Agreement No. DE-FC21-86MC10637

TABLE OF CONTENTS

COAL SCIENCE

1.0 OBJECTIVE AND GOALS

The general "Coal Science" objective of the North Dakota Mining and Mineral Research Institute (MMRRI) is directed towards a fuller utilization of energy and energy-related data, currently available as published and unpublished documents, to better evaluate resource potential through a thorough knowledge and understanding of the geologic context of the resource.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 is to be implemented through computer-based data management systems involving specific field examples. The focus of the first phase of the project is to establish the computerized basis for reevaluating, or evaluating locally for the first time, North Dakota's lignite resource in a stratigraphic and paleontologic context. Specific fundamental goals include the construction of flexible, relatable data base designs and the testing of these designs through practical examples.

2.0 ACCOMPLISHMENTS

All facets of the goals were initiated and completed during the first year of the project, except for the drilling and logging of test holes in western North Dakota (see below). Goals undertaken and completed include: 1) inventory of available computer and computer-related (e.g., peripherals) hardware; 2) review and acquisition of computer hardware, peripherals, and data-capture systems; 3) review and acquisition of software for data management use; 4) design of data management systems for coal and coal-context data; 5) input of data concerning coal bed stratigraphy and paleontology; 6) review and acquisition of field and laboratory equipment for use in test area studies; 7) geologic and paleontologic preparation of test area project samples; and 8) publication and presentation of "Coal Science" system-based projects concerning the lithic and temporal correlation of coal-bearing strata in the northern Great Plains. The completion of the drilling portion of this project was delayed because of scheduling problems associated with other projects resulting from the August start of the "Coal Science" project and because of delays in obtaining archaeological clearance of the chosen drill sites. Final approval by the Forest Service has been given to drill at two sites (described below).

2.1 Computer Data Management Hardware Acquisitions

Through the course of the year, a computing system was established using "old" and newly acquired components. All of the components initially considered in the "Coal Science" data management system are linked and utilized in the analysis and interpretation of coal resource and geologic context data. The main data management computer is a Gateway 2000, an IBM clone. The computer is a 386, 25-mHz machine, with the appropriate math coprocessor and two 150-mb hard drives. Memory caching and disk management procedures make this machine relatively inexpensive, yet powerful and fast.

A previously acquired MMRRI computer is used for data input by MMRRI staff. This machine is a Standard 286 with a math coprocessor and 40-mb hard drive. The 286 computer is cabled to the main data management computer for data transfer and for directly outputting various types of graphics and text data. As available, various other 386 computers are used for the input of data.

The data and programming on the main data management computer is archived using an Everex external cassette tape backup system. Data can be outputted to an 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 (examples given in Appendix II). Input devices include a previously acquired large format GTCO digitizing board and a video capture system (see below). Communications devices include a hardware link to the mainframe computing system at the University of North Dakota and a previously acquired MultiTech modem.

The video system 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 (12.5-73 mm zoom), and TOYO diopters and is displayed on a high-resolution SONY Trinitron monitor. Photographs of the monitor or video image are acquired from a SONY thermal printer. The video system uses specialized programming, such as Jandel's JAVA program, to "capture" black and white 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 resolved by establishing protocol to reconfigure the hardware for different applications. Thus the video system runs under its own configuration to resolve its hardware specific requirements. The video system can capture images for analysis at three scales or levels of magnification: 1) large or macro size 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 micro-size, effectively two-dimensional objects (less than 1 mm in size). Large scale objects can be viewed directly with the Cohu camera system. The camera and attachments are mounted directly to a modified 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 close-up study of large specimens, require macrophotography. To achieve the ability to examine samples of this size, a video-ready Olympus stereomicroscope was acquired. This imaging system provides magnification from about 2.5x through about 50x. The micro-size range of objects is studied under thin-section with high-powered stereomicroscopes. A Zeiss microscope is available at UND-EERC for this purpose. A video/microscope coupler, specific to this project and imaging system, was manufactured by Diagnostic Instruments to permit video numerical analysis of objects magnified up to 500x.

2.2 Other Equipment Acquisitions

One additional piece of equipment was acquired to improve the processing of samples and their analysis: RAYTECH 10-inch rock slab and trim saw for the preparation of geologic cores, lithic samples, and paleontologic specimens.

2.3 Computer Data Management Software Acquisitions

MMRRI has decided to develop a data management system using "off the shelf" programs on the basis of the following factors: 1) The rapid and continued development of sophisticated commercial data base management programs, 2) the substantial cost of in-house development of computer programming, and 3) the difficulty of assessing MMRRI's overall long-term computer programming needs. Thus various programs were acquired and tested to determine the best data management system for use at MMRRI. The general data management philosophy has been to grow into a system, rather than force an approach. The basic requirements of the system are that 1) program designs are easily modifiable, and 2) data once entered is transferrable to other programs as new applications arise.

The approach taken in data base design and programming is to utilize a combination of flat or semi-relational data managers with fully relational data managing systems. This approach provides a powerful, yet easily modifiable, programming foundation, compatible with MMRRI user needs. The programming chosen for this purpose are Symantec's Q&A and Borland's PARADOX. Both programs are powerful but differ in their approach to data management applications. Q&A is a "semi-relational" data manager and presently serves as the main program for inputting, manipulating, and displaying lignite, stratigraphic, and paleontologic data. Q&A differs from many programs (considered both a weakness and a strength depending on your application) in its use of the "form" (versus the table) as the basis for data storage. Q&A's main strengths are in its 1) ease of data manipulation (within and between forms or as reported in tables), 2) effectively unlimited field length, 3) use of internal and multiple external (semi-relational) 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. Q&A contains a word processor that can be employed to utilize information from data bases within its "file" environment. 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.). Examples of file data processed through Q&A's word processing environment are given in Appendix II. The cleverness of the overall Q&A program design permits the effective use of its most advanced functions by less computer-literate staff. Relational and programmable programs, such as PARADOX, which are also simple to use at their basic level, become relatively complicated for interactive daily use, even in normal (for MMRRI) reporting, where applications or needs change frequently. Q&A works well as an on-line system for data inputting, updating, and retrieval, where applications vary (as the rule) considerably. PARADOX, ultimately more powerful, is specific-application oriented, which at this point in MMRRI data management considerations is less important than flexibility. Compared to major-market data base 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 very inexpensive and has now been acquired by a number of

MMRRI users interested in expanding their data base applications. PARADOX is used with the MMRRI data management system for certain data filing maintenance applications. PARADOX and Q&A files can be exchanged using a common dBASE or ASCII interface.

Besides more or less standard file information retrieval and reporting, Symantec's Q&A program is used to generate reports of information for essentially automatic use in other programs. Most application specific programs are not inherently good data managers as they do not provide the flexibility of a full data base management system such as Q&A. Thus the approach to data management and manipulation is to utilize data management systems to provide the basis for data retrieval and reporting and to export data to other programs for specific applications. Other programming, if not inherently compatible, can be modified to permit the exchange of data. For example, modifications were made to a public domain program (STRATA/STRATCOL) to facilitate the expedient, high-quality laser print output of stratigraphic sections (Appendix III). Data for these sections are maintained in Q&A in the file *UNIT.DTF (described below). A number of modifications are possible depending on the needs of the user. Similar applications are being considered for LOGGER by Rockware and STRATIFACT by GRG, which are also programs with specific geologic applications.

STRATIFACT was acquired (through other funding) for the display and analysis of geologic section data and their correlation. STRATIFACT is designed for the management and display of discontinuous strata as typically found in coal-bearing nonmarine and marginal-marine environments. A new version of the program, which will better serve MMRRI project needs, will not arrive until after the current project year. The pre-"beta" version of the program, reviewed in the fall of 1989, was apparently a long way from completion, with GRG substantially underestimating the time to availability. A utility module was also acquired from GRG that will permit the transfer of information to and from the U.S. Geological Survey's NCRDS coal data management program. MMRRI Q&A data bases (described below) will be linked with STRATIFACT (based on available information) through a dBASE interface.

Other geologic programs acquired for "Coal Science" applications include LOGGER by Rockware and various "GS" products (e.g., GSLITH) by the U.S. Geological Survey. LOGGER is a versatile, if laborious, data management program for geologic section information. Data is stored in ASCII format, which can, in part, be extracted for use elsewhere or derived from Q&A data files. The GS-products were acquired through nominal charge and will be reviewed, along with STRATIFACT, for specific applications. The GS-products have certain limitations for the user who is not computer-oriented or who does not use the program on a regular basis.

Video-capture and analysis programs that have been acquired for use with the hardware described above include JAVA by Jandel and MORPHOSYS by Dr. Chris Meecham of the University of California-Berkeley. To date, applications have focused mainly on paleontological specimens to determine methods for improving the accuracy and speed of taking standard measurements. In addition, video imaging provides the opportunity to effectively take "instant" photographs of specimens. This photographic technique saves a tremendous amount of time over conventional photography for sample documentation. Like conventional photography, but in its own peculiar way, video photography is extremely light sensitive. To facilitate the control of lighting during video photography, a standard MP3-type copy stand was rewired so that each of the four high-intensity lamps could be individually regulated. Although development of video-capture applications has just begun, it offers great promise in the numerical analysis of a variety of samples and irregular two-dimensional images (e.g., geophysical logs) and in the incorporation of video images into other programs for display or additional analysis.

The spreadsheet program QUATRO PRO, by Borland, was acquired to handle sample numerical data management and analysis. QUATRO PRO was chosen over LOTUS-123, in part, because it provides greater control in reporting data and in its better graphics. Technical graphics and statistical programs acquired under other funding will also be used in data analysis and display. For example, NTSYS-pc, by Applied Biostatistics, is a numerical taxonomy and multivariate analysis system of programs. NTSYS-pc was acquired for numerical analysis of paleontologic data and will be used in conjunction with data obtained through video imaging.

2.4 Data Base Designs

During the year, data base design features were considered relative to potential needs. Data bases were designed and frequently modified for use with stratigraphic and paleontologic data for specific applications. General approaches were determined to different types of data and are discussed below. Examples of geologic section and paleontologic sample data base designs are given in Appendix I.

At present, four major file-types are employed to handle geologic and paleontologic resource information. Additional files permit access to related data of a unique nature, such as map information (e.g., publication, revision information, contour interval) and coding information, such as words, abbreviations, or terms that have special meaning for sort routines. The four main file-types include: 1) geologic section or geologic 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 or PRB for the Williston or Powder River Basins. Both data files with these prefixes have the same data base design and can be automatically merged into one large data base if required.

The *MNOS files contain information on the location of geologic observations, such as surface and subsurface measured sections (Appendixes I and II). The *MNOS form contains six general field categories in 98 fields, including 21 code fields for specialized sort routines. *MNOS field categories include: 1) reference information, 2) numbering systems associated with record, 3) location and landowner information, 4) section thickness and elevation information, 5) litho- and chronostratigraphic information, and 6) sample/specimen information. Reference information fields contain data on the source of the information (i.e., citation), including 1) authorship, 2) source of data, 3) project chief, 4) institutional or agency affiliation of the project chief, 5) location of observation in cross-section panels, and 6) type of observation (e.g., surface measured geologic section). Numbering systems associated with the record include: 1) UND-EERC-MMRRI "M-number;" 2) a reference number, associated with the source of information, such as a number specifically associated with the publication or in-house report of the geologic section; 3) field number, usually referring to the original number used during field work; and 4) institutional number, referring to numbering systems employed by various agencies or institutions (e.g., NDSWC 4252 = North Dakota State Water Commission number 4252); 5) section name, if any (e.g., Tepee Buttes section). Location fields contain information ranging in scale from general political boundaries to site-specific coordinate systems: 1) nation, 2) region, 3) field area, 4) state, 5) county, 6) map reference, 7) township and range location, 8) footage from section lines, 9) longitude and latitude, 10) UTM coordinates, 11) state grid coordinates, 12) property owner information, and 13) general location comment field. *MNOS files use the MAPS file as an external lookup table to import map reference information. Section thickness and elevation information are contained in fields that automatically convert metric to English measurements, footage error associated with elevation interpretation, and initials of interpreter of elevation. Litho- and chronostratigraphic information is contained in fields that reference: 1) the geologic age of the measured section or observation; 2) the formations represent in the section; 3) the thickness of the formations represented in the section; 4) the completeness of the formation at this location; 5) a general listing of the named beds in the section; 6) specific reference to a particular bed, its original name (revision from field or published identification), and unit number in the section; and 7) general stratigraphic comment field. This form also contains sample and photographic information concerning the entire section, including reference numbers for 1) fossil localities, 2) lithic samples, and 3) photographs of the section.

The corresponding or companion *UNIT file has 44 fields specific to geologic section unit reference, measurement, and description. 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. Reference fields include: 1) M-number, 2) source of information, 3) unit number, 4) unit (bed) name, 5) original bed description, 6) formational assignment of unit, 7) and sample number(s) pertaining to the unit. Measurement fields record individual unit thicknesses and permit calculations to be made to derive unit thicknesses from a variety of original information types, depending on the nature of how the section was measured. Methods of deriving unit thickness include: 1) simple inputting of original data from described, measured sections (with conversions between feet and meters); 2) calculation of unit thicknesses by measuring illustrations of geologic sections for which original data no longer exists; and 3) calculation of unit thicknesses from surface geologic sections constructed by pace and compass techniques (utilizing dip control). Description fields contain information derived from the original description or illustration of the geologic section. As noted, this data base includes a large field that permits the quotation of the description of the unit as originally interpreted. The remaining fields contain information specific to different lithic aspects or characteristics of the units. Standard field types include: 1) primary rock type, 2) rock-type modifiers, 3) fresh and dry colors (GSA rock color chart), 4) sedimentary structures, 5) grain size sequences, 6) weathering profile, 7) depositional environment, and 8) fossil-indicated environment. Other fields are added as needed to manage information for specific projects or to set up data (through internal lookup tables) for loading into other programs (e.g., coding for the illustration of geologic sections). As examples, *UNIT is currently set up to generate reports for the program STRATA/STRATCOL and for NCRDS data base formats.

*LOC files contain records on the location of fossil localities and are specifically designed for micro- and macro-fossil specimens. The *LOC file is similar to *MNOS files in general design, containing 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 file MAPS for map reference information. Specialized locality fields include information on 1) litho- and chronostratigraphy, 2) collecting history, and 3) the fauna. Stratigraphic fields contain information concerning: 1) the formation and member to which the locality can be assigned, 2) the original formation used by the discoverer of the locality, 3) the elevation of the locality, 4) the footage determination of the horizon of the locality within the formation (e.g., from top or bottom), 5) the level or interval of the locality relative to other formational contacts and marker beds, 6) the measured section and unit numbers (*MNOS, *UNIT) to which the locality belongs, 7) the age of the locality, and 8) a an extended comment field for additional stratigraphic considerations. Information concerning the collecting history of the locality includes: 1) the discoverer(s) and date of discovery, 2) collector(s) and date of collecting, 3) field party chief and institutional or agency affiliation, and 4) the repository for the collections. Faunal information about the locality includes: 1) fossil groups represented at the locality (e.g., mammals, microfossils, mollusks, etc.), 2) a faunal list of identified taxa, 3) the name of the individual identifying the fossils, and 4) a faunal comment field concerning the preservation of the fossils.

The companion *SPP file records information on the identification of taxa at a particular locality. Field types include: 1) taxon identification, 2) a simplified classification of the taxon, 3) repository and specimen numbers, and 4) a number of specimens and identification comments. Both old and revised identifications are recorded to provide a history of study on specific specimens and taxon names. The file *SPP uses the *LOC file and MCLASS files as external lookup files. Using *LOC files, the stratigraphic range of a taxon can be determined through a merge of the components of the two files. Using the MCLASS file, a simplified classification of a taxon can be automatically imported into *SPP to provide a means to summarize stratigraphic data on higher taxonomic categories.

Future changes in data base management techniques provided by software vendors will permit greater power in design capabilities and will be effectively utilized by the current data management approach.

2.5 Data Input

Data were entered in all of the four main file types (ie., *MNOS, *UNIT, *LOC, and *SPP) for the test areas in western North Dakota and in other coal strata study areas. External lookup files were also constructed that maintain information on map reference data (MAPS) and fossil classification (MCLASS). Other files record information on related information and include the following files: 1) overall locality register (LOCREG), 2) type-specimen data (TCKZOIC), 3) specimen numbers and institutional repositories (SPEC_NO), 4) taxon coding (TAXON_NO), and 5) reference bibliography (BIB).

The *MNOS and *UNIT files, representing measured section and other geological observations, contain thousands of forms from only the small test areas in selected parts of North Dakota. The efficiency and effectiveness of these data bases will be tested as more data is incorporated into the system. Areas of specific interest include Slope and Bowman counties in southwestern North Dakota and the Fort Union area in Williams and McKenzie counties along the Missouri River. As the data bases increase in size, more efficient methods will need to be used to portray graphically the distribution of data. Locality (*LOC and *SPP files) information has also been inputted for these areas and continues to be augmented. Locality information has also been inputted for the Powder River Basin for the purposes of determining the age relations between the coal-bearing strata of this basin with that of the Williston Basin. MAP data has been entered for North Dakota, Montana, Wyoming, and portions of southernmost Saskatchewan. Additional MAP file management is underway. USGS map data has been and continues to be downloaded from magnetic tapes into Q&A files for greater ease of use.

2.6 Sample Preparation

Geologic and paleontologic samples of importance to interpreting the geologic context of coal-bearing strata in the test areas were prepared for study. Sample analysis included traditional and recently available techniques (video-capture) to provide stratigraphic, environmental, and biochronologic information.

2.7 Drilling and Test Area Studies

The drilling and logging of test holes in selected test areas in western North Dakota was proposed to 1) provide fundamental information on the stratigraphic problems associated with the 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. Two sites were chosen: one in northwestern Slope county and the other in southwestern Golden Valley county, North Dakota (Appendix IV). The strata represented by these sites include strata of the 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 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. Appropriate permit forms were approved in the last part of June 1990. Bid invitations were also requested, and one bid was accepted. Due to the delay in receiving archaeological clearance for one of the proposed sites, the bid is no longer valid. The bid process, if necessary, will be undertaken again in August or September, with drilling to occur in September, if at all possible. Bid specifications were modeled after those required by the North Dakota State Water Commission.

2.8 Papers and Presentations

Papers, presentations, and illustrations were prepared throughout the year and utilized data inputted into the data base management structure described above. The flexibility of data retrieval and reporting methods permitted medium-sized data to be organized for convenient interpretation. Topics for which the "Coal Science" data management system was employed included chronostratigraphy of lignite-bearing strata in the Paleocene and lower Eocene of the Fort Union Group in the Williston and Powder River Basins of North Dakota, Montana, and Wyoming (see Appendix V).

2.9 Other Studies

Other studies are underway at MMRRI that utilize various components of the data base management and video systems described above. These studies include 1) NCRDS data management and assessment at MMRRI, 2) a master's thesis project by Wes Peck (UND-Department of Geology and Geological Engineering) on "The stratigraphy and sedimentology of the Sentinel Butte Formation (Paleocene) in south-central Williams County, North Dakota," and 3) a Ph.D. project by Tim Kroeger (UND-Department of Geology and Geological Engineering) on "Paleoecology of Paleocene palynomorph assemblages from the Bear, Lebo, and lower Melville Formations in the Crazy Mountains Basin of south-central Montana and the Ludlow, Cannonball, and Slope Formations of the Williston Basin of southwestern North Dakota." Both projects provide litho- and chronostratigraphic data of importance to the correlation of coal-bearing strata specific to the test areas in western North Dakota.

3.0 SUMMARY AND CONCLUSIONS

The general "Coal Science" objective of the North Dakota Mining and Mineral Research Institute (MMRRI) is directed towards more effective use of geologic observations specific to the correlation and assessment of coal-bearing strata. The effective and efficient utilization of these observations requires streamlined but flexible user-oriented data management programs incorporating straightforward data inputting and summary data output in the form most convenient to the user. Substantial amounts of currently useful and historically invaluable geologic data bearing on the correlation of coal beds is 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 is to implement, through computer-based data management systems, specific test area field studies that utilize all currently available information for the assessment of efficient data base management techniques in the evaluation of specific coal correlation problems. This project is specific to fundamental coal resource and geologic stüdies undertaken by MMRRI. There is no attempt to duplicate the general needs of a national data base resource management program which, by its very nature, must approach coal correlation at a more general level, dependent entirely on the nature of data inputted to it. The data bases described above are multidisciplinary and aimed at resolving specific questions a litho-, bio-, and chronostratigraphic correlation.

The focus of the first phase of the project is to cstablish the computerized basis for reevaluating North Dakota's lignite resource in a stratigraphic and paleontologic context. Specific goals, as represented by project milestones, included the following categories:

- acquisition of computer-related hardware
- review of available approaches to data management of geological data
- construction of geologic and paleontologic data base designs
- data input for assessment of data base designs
- relating data base systems.

All of these goals were met. Using new computing equipment and machines previously available, data bases were designed to manipulate thousands of geologic and paleontologic records. These designs have proven to be efficient in the resolution of specific geologic problems, both on a day-to-day basis, but also in meeting specific project needs (see Appendix IV). Much more data is available to enter to augment coal resource projects currently underway. Additional data will further test the efficiency of designs of established data bases. All of the data base files are related to one another and to auxiliary files either through programming or keywords. Relating data bases in this manner permits far more flexibility than would otherwise be permitted through larger (but less detailed) data bases.

One project goal for the last year that was not met was the completion of the drilling and logging of test holes in western North Dakota. The drilling of these holes does not directly affect data base design or construction and thus does not adversely affect the progress of this "Coal Science" project. However, the ability to interpret the entered geologic and paleontologic data has been hindered. The sites described above (see also Appendix IV) will be drilled in September, barring any further complications.

4.0 APPENDIXES

4.1 Appendix I

File Design in Q&A

4.2 Appendix II

Q&A File Data Processed through Q&A's Word-Processing Environment

4.3 Appendix III

STRATA/STRATCOL Output (Exported Q&A Stratigraphic Data), Measured Section MMRRI-M0744 by Van Alstine (1974)

4.4 Appendix IV

Drilling Sites in Western North Dakota

4.5 Appendix V

Publications

4.1 Appendix I

File Design in Q&A

4.1.1 M-number geologic observation location and general stratigraphy file form (see Appendix 4.2 for example)

4.1.2 M-number stratigraphic section units file form (see Appendix 4.2 for example)

4.1.3 Section M0744 example of stratigraphic units data derived from Q&A form 4.1.2 (this data is illustrated in Appendix 4.3)

4.1.4 L-number paleontologic observation location, general stratigraphy, and general identification form (see Appendix 4.2 for example)

4.1.5 L-number taxon identification form (see Appendix 4.2 for example)

APPENDIX I Form 4.1.1

Mno: REF: DATE:
P: PAG: LOG:
Fno: REF#: NAME:
INST: #: LOGt: D: U: D: S:

NAT: REG: FIELD: ldg: ent:
ST: CO: QD: YR: SR: CI:
QQ: SEC: T: NS: R: EW: SC: TC: RC:
X: FNS: #3: FEW: #4: Z: Ng: UTM: Eg: UTM:
LG: LT: CNS: CO#: CEW: CO#:

SC-TK/FT: BOT-EL: TOP-EL: +/-: INT: S/:
SC-TK/M : B-EL/M: T-EL/M: O: FD: XS: C:

E: EP: A: AGE: F1: FM1: TK1:
B: BD: U#: F2: FM2: TK2:
ORG-BD: 1: 2: 3: F3: FM3: TK3:
BEDS:

refBOSS: from:
secDONEon: intBY:

STRAT:

LOC:

PROPowner:

COM:

FS: Lno:
LS: LS#:

PIC:

M#: REF: DATE:
SC: PAG: LOG: 1990/07/31
ST: REG: ent:

U#: BED: FM: OUM: f:
DV: x: SCALE: DIP: DIPrad:
+: COM: PACE: fctval:
TK: TK/M: SC-EL/B: SURF: U-TK:
SC-TK: SC-EL/T: SURF-T: SC-TK:
DESC:

ROCK : RK/M:
LITH : SYM: WEA/P:
COL/F: COL/D:
SEQU : S/S :
ENVIR: COM2:

Lnos : F-ENVI:
RK-S :

NCRDS specific fields UQ:
----

priLITH: modLITH: COLOR:

GRsize: GRshape: MINERAL:

BEDDING: CONTACT: FOSSILS: FRACTURES: JOINTS: CLEATS:

WILD1: WILD2: COMMENT:

M0744 (Van Alstine, 1974)

MMRRI Sect. No.	Sect. Unit No.	Unit THICK ft	Feet Above Base of Section	Meters Above Base of Section	Original Lithologic Description
M0744	042	0.000	244.748	74.599	top of section
	041	3.412	244.748	74.599	"Mudstone; poorly consolidated; dusky yellow where fresh (moist), yellowish gray where weathered (dry); blocky on fresh surface, swelling on weathered surface; gradationally interbedded with sand"
	040	10.170	241.336	73.559	"Sandstone; poorly consolidated; dusky yellow where fresh (moist), yellowish gray where weathered (dry); fine to medium grained, poorly sorted and rounded. faint cross bedding; gradationally interbedded with dark shaley lenses (1-cm thick); 2.8 m below top of unit is a thin (0.3 m), dark brown, almost ligniti. shale"
	039	22.966	231.166	70.459	"Concealed (sandy slope wash and vegetation)"
	038	0.984	208.200	63.459	"Sandstone; well indurated; dusky yellow brown; concretionary; fine-grained muddy sand; common plant fragments; lenticular bench former"
	037	5.905	207.216	63.159	"Mudstone; poorly consolidated; dusky yellow where moist, yellowish gray where weathered (dry); grades into muddy fine- to very fine-grained sandstone toward bottom; scattered lenticular muddy sandstone concretions in middle of unit"
	036	0.984	201.311	61.360	"Lignite"
	035	9.514	200.327	61.060	"Mudstone; poorly consolidated; dusky yellowish brown where moist, pale yellowish brown where weathered (dry); blocky on fresh surface, with abundant plant fragments; gradational interbedding into a muddy sand, down into predominantly sand; yellowish brown where moist, pale yellowish brown where weathered (dry)"
	034	2.723	190.813	58.160	"Mudstone; well consolidated; dark yellowish brown where moist, pale yellowish brown where weathered (dry); blocky on fresh surface; plant fragments common"
	033	3.478	188.090	57.330	"Siltstone; well consolidated; grayish brown where moist, pale yellowish brown where weathered (dry); massive; plant fragments abundant (seed pods?...)"
	032	4.495	184.612	56.270	"Lignite (quite possibly Yule Lignite of Hare [sic] (1928, p. 26)"
	031	3.281	180.117	54.900	"Lignitic mudstone; poorly consolidated; dark grayish brown where moist, light grayish brown where weathered (dry); bentonitic; lignite particles abundant"
	030	0.131	176.836	53.900	"Lignite"
	029	3.937	176.705	53.860	"Mudstone; poorly consolidated; dusky yellow where moist, yellowish gray where weathered (dry); massive, grading into muddy sand thiny [sic] bedding in places; lignitized plant particles and marcasite nodules abundant at base of unit"
	028	3.117	172.768	52.660	"Lignite"
	027	7.152	169.651	51.710	"Mudstone; poorly consolidated; dark yellowish brown where moist, grayish brown where weathered (dry); blocky on fresh surfaces; thinly bedded; lenticular mudstone concretions (0.05 m thick) present 1.5 m below top of unit; below this zone unit grades into interbedded mud and sand; plant fragments abundant"
	026	2.297	162.499	49.530	"Lignite"
	025	3.773	160.202	48.830	"Sandstone; poorly consolidated; dusky yellow where moist, yellowish gray where weathered (dry); very fine- to fine-grained; interbedded with lenses (0.1 cm thick) of mudstone at top, becoming massive toward bottom; lignite particles and lignitized plant fragments abundant throughout unit"
	024	1.936	156.429	47.680	"Lignite"
	023	13.779	154.493	47.089	"Cannonball Formation: Sandstone; poorly consolidated; moderate yellowish brown where moist, yellowish gray where weathered (dry); very fine- to fine-grained; thinly bedded, grading into interbedded sandstone and mudstone toward the bottom

(ABVbtLIST.MS-WBUNIT.DTF) 8/7/90 9:47 am

M0744 (Van Alstine, 1974)

MMRRI Sect. No.	Sect. Unit No.	Unit THICK ft	Feet Above Base of Section	Meters Above Base of Section	Original Lithologic Description
					of the unit; marcasite nodules and thin (0.03 m) tabular concretions at base of unit"
	022	18.865	140.714	42.890	"Mudstone; poorly consolidated; dark yellowish brown where moist, light grayish brown where weathered (dry); thinly bedded with some sand at the top, becoming blockier and almost a lignitic mudstone at bottom of unit...fossiliferous, common to abundant...from 0.52-0.80 m above dark mudstone marker bed [3.5 m below top]...as lenticular patches...in lower 1-1.5 m of unit...."
	021	2.789	121.849	37.140	"Lignite"
	020	18.044	119.060	36.289	"Mudstone; poorly consolidated; olive gray where moist, light gray where weathered (dry); bentonitic, with "popcorn"-like weathered surface in upper portion of unit, grading into interbedded sand and mudstone about 4.5 m below top of unit; unidentified insect parts (probably contamination) and plant fragments present through unit"
	019	4.921	101.016	30.790	"Mudstone; poorly consolidated; very dark brown (almost lignitic) where moist, light yellow brown where weathered (dry); bentonitic, with a "popcorn"-like weathering surface; thinly bedded throughout unit; plant fragments (seed pods?...) present"
	018	3.281	96.095	29.290	"Lignite"
	017	0.984	92.814	28.290	"Sandstone; well indurated; dusky yellow brown when weathered, fine-grained muddy sandstone"
	016	3.281	91.830	27.990	"Concealed; (sandy slope wash and vegetation). Includes the lateral distance from the bottom of the first half of the composite section, west 0.8 km to the top of the Little Missouri River cutbank where the second half of the composite section was measured"
	015	8.202	88.549	26.990	"Sandstone; moderately consolidated; dusky yellow brown where moist, light yellowish brown where weathered (dry); fine- to medium grained; massive, forming an almost vertical face; capped by a 0.5 m, well indurated, tabular, sandstone concretion"
	014	7.546	80.347	24.490	"Mudstone; poorly consolidated; yellowish brown where moist, light yellowish brown where weathered (dry); predominantly mudstone at top of unit, grading into interbedded mudstone and sandy mud toward bottom; thin (0.01 m) lenticular mudstone concretions from the top of the unit"
	013	3.773	72.801	22.190	"Lignite and lignitic mudstone"
	012	1.936	69.028	21.040	"Mudstone; poorly consolidated; dark yellowish brown where moist, light yellowish brown where weathered (dry); blocky on fresh surfaces; plant fragments abundant (seed pods?)..."
	011	1.312	67.092	20.450	"Sandstone; poorly consolidated; dusky yellowish brown where moist, light yellowish brown where weathered (dry); fine- to medium-grained; poorly sorted"
	010	2.198	65.780	20.050	"Lignite"
	009	1.312	63.582	19.380	"Sandstone; poorly consolidate; dusky yellowish brown where moist, light yellowish brown where weathered (dry); fine- to medium-grained; lignite particles abundant"
	008	1.312	62.270	18.980	"Lignite"
	007	10.335	60.958	18.580	"Sandstone; poorly consolidated; dark yellowish brown where moist, yellowish gray where weathered (dry); fine- to medium-grained; interbedded with mudstone in middle of unit, grading into mudstone at bottom of unit..."

(ABVbtLIST.MS-WBUNIT.DTF) 8/7/90 9:47 am

M0744 (Van Alstine, 1974)

MMRRI Sect. No.	Sect. Unit No.	Unit THICK ft	Feet Above Base of Section	Meters Above Base of Section	Original Lithologic Description
M0744	006	3.281	50.623	15.430	"Cannonball Formation?: Mudstone; moderately consolidated; dark yellowish brown where moist, light grayish brown where weathered (dry); thinly bedded, but block on fresh surfaces; carbonaceous; abundant plant fragments present...unit is interpreted to be the farthest westward extension of the lowest tongue of the Cannonball..."
	005	5.774	47.342	14.430	Lignite (T cross lignite of Hares 1928); To west, burning lignite has baked overlying mudstone; bivalve and gastropod impressions common in 'scoria'"
	004	19.357	41.568	12.670	"mudstone; poorly consolidate; dark reddish brown where fresh (moist), light yellowish brown where weathered (dry); blocky on fresh surface; interbedded with less sand; insect parts...single immature gastropod found"
	003	6.135	22.211	6.770	"lignite"
	002	9.514	16.076	4.900	"sandstone; poorly consolidated; yellowish gray where moist, light yellowish gray where weathered (dry); fine grained; interbedded with mudstone in places"
	001	6.562	6.562	2.000	"concealed (sandy slope wash and vegetation)"
	000	0.000	0.000	0.000	base of section "at level of Little Missouri River"

(ABVbtLIST.MS-WBUNIT.DTF) 8/7/90 9:47 am

Lno: REF: DATE:
P: PAG: LOG:
Fno: REF#: NAME:
INST: #1: #2: FS: U: U:

NAT: REG: FIELD: ldg: ent:
ST: CO: QD: YR: SR: CI:
QQ: SEC: T: NS: R: EW: SC: TC: RC:
X: FNS: #3: FEW: #4: Z: Ng: UTM: Eg: UTM:
LG: LT: CNS: CO1: CEW: CO2:
SLD: PRT:

EP: AGE: FM: MB: E: A: F:
L: LEVEL: 1: FC: CT: EL: +/-:
V: ABV-B: 2: F1: M1: INT: S/: O:
W: BLW-T: 3: F2: M2: M#: U#:
FM(ORG): FD: XS: C:

refBOSS: from:
DYR: M/D: DISC:

MKR-C:
STRAT:

LOC:

COM:

CHIEF: of:
CYR: M-D: COLLR:

COLLN: C/INST:
FAUNAL(COM):

IDER:
IDS

APPENDIX I Form 4.1.5

Lno: ST: REG: AGE: A: DATE:
P: ENV: WBSPCOM: ent: LOG:
LOC(COM):

CLS: UG: TYP: U1: U2: U3:
FAM: FC: REP: S#: C:

GEN: C1: OgGEN: C5:
SbGEN: C2: OgSBG: C6:
SPP: C3: OgSPP: C7:
SbSPP: C4: OgSBS: C8:
IDER: OgIDER:

REF: OgREF:
PAG: OgPAG:

#S: SPP(COM):

G-NOM:

4.2 Appendix II

Q&A File Data Processed through Q&A's Word-Processing Environment

The form design and data field names given below are independent of file design. Any number of versions and presentation configurations are possible without affecting data base design or inputting protocol.

4.2.1 Example of a word-processed *MMOS form (geologic observation location and general stratigraphy form) (see Appendix 4.1 for file form example).

4.2.2 Section M0744 example of a word-processed *MNOS form (geologic observation location and general stratigraphy form).

4.2.3 Section M3131 NCRDS example of a word-processed *MNOS form (geologic observation location and general stratigraphy form, includes stratigraphic *UNIT data).

4.2.4 Example of a word-processed M-number stratigraphic *UNIT form (see Appendix 4.1 for file form example).

4.2.5 Section M0744 example of a word-processed M-number stratigraphic UNIT form.

4.2.6 Example of a word-processed *LOC form (paleontologic observation location, general stratigraphy, and general identification form) (see Appendix 4.1 for example).

4.2.7 Locality L4962a example of a word-processed *LOC form (paleontologic observation location, general stratigraphy, and general identification form). This locality occurs in *MNOS section M0744.

4.2.8 Example of a word-processed *SPP form (species identification form).

4.2.9 Locality L0429 example of a word-processed *SPP form (species identification form).

WILLISTON BASIN MMRRI M-number LOCALITY FORM

J.H. Hartman, UND-EERC-MMRRI

data entered on:

printed: 8/7/90

Mno: example REF: ,

FIELD#: REF#: NAME:

INST: #: REF BOSS:

LOG TYPE: FOSSILS: SAMPLES: BOSS from:

Completed on: Interpreted by:

==

NAT: REG: FIELD AREA:

STATE: COUNTY: QUAD: YR: SER: CI:

TWP/RGE: sec. , T. ., R. . SECcode: LAT/LONG ldg:

FSL in FT: FSLcode:

SECTION THICKNESS in FT: TOP ELEV: BOT ELEV: +/-: INT:

EPOCH: AGE: X-SECTION: COLUMN:

BED NAME: FM: THICK: FMc: C:
UNIT #: OTHER FM: THICK: FMc: C:
ORG-BED NAME: OTHER FM: THICK: FMc: C:

BEDS:

STRAT:

LOC:

COM:

PROPERTY OWNER:

Fossil Locality nos:

Lithic Sample nos:

Field Photos:

WILLISTON BASIN MMRRI M-number LOCALITY FORM

J.H. Hartman, UND-EERC-MMRRI
data entered on: 1988/09/22
printed: 8/7/90

Mno: M0744 **REF:** Van Alstine (1974), p. 71-77

FIELD#: JBVA-01 **REF#:** **NAME:**

INST: **#:** **REF BOSS:** Cvancara, A.M.

LOG TYPE: MS **FOSSILS:** B/F **SAMPLES:** **BOSS from:** University of North Dakota

Completed on: 1972/07/25 **Interpreted by:** Van Alstine, J.B.

===

NAT: USA **REG:** WB-LMR **FIELD AREA:**

STATE: ND **COUNTY:** Slope **QUAD:** Three V Crossing **YR:** 1979 **SER:** 7.5 **CI:** 20

TWP/RGE: S SW SW sec. 10/15, T. 135 N., R. 105 W. **SECcode:** 15 **LAT/LONG ldg:** 46103

FSL in FT: **FSLcode:**

SECTION THICKNESS in FT: 244.751 **TOP ELEV:** 2844.748 **BOT ELEV:** 2600.000 **+/-:** 10 **INT:** JHH

EPOCH: PAL **AGE:** **X-SECTION:** A24 **COLUMN:** D18

BED NAME:	**FM:** Slope	**THICK:** 203.672	**FMc:** 2	**C:**
UNIT #:	**OTHER FM:** Cannonball-U	**THICK:** 18.865	**FMc:** 2	**C:** C
ORG-BED NAME:	**OTHER FM:** Ludlow	**THICK:** 22.211	**FMc:** 1	**C:**

BEDS: unnamed [T Cross]; T Cross [LCP]; 9 unnamed [LCP (2); UCP; E Yellow Mkr, Straight SS; UCP; Oyster; Oyster cly; No. 1 z; Yule z]; unnamed; [chl 11]

STRAT: Represents a nearly complete section of the Slope Formation.

LOC: "Composite section; upper one half measured on southwest-facing hillside exposure, west side of Little Missouri River (about 0.8 km west of river) on east side of small auto trail, SW 1/4 SW 1/4 sec. 10...lower one-half of section measured on south-facing cutbank exposure, west side of Little Missouri River, NW 1/4 NW 1/4 sec. 15...." Base of section at Little Missouri River.

COM: "The upper one half of the section is similar to the section given by Cvancara (1965, p. 250-257)."

PROPERTY OWNER: U.S. Forest Service

Fossil Locality nos: L4962a-b (F); L4962c (CNBL-L); L4963a-b (CNBL-U)

Lithic Sample nos:

Field Photos:

USGS NATIONAL COAL RESOURCES DATA SYSTEM - STRATIGRAPHIC DATA FORM - USTRAT

printed: 1990/08/07

POINT ID: M3131 **GEOLOGIST**: NDMI-Schmit CR **DATE**: **CONFID**:

QUAD+SER: West Rainy Butte 7.5 **SOURCE**: USGS/NDGS. **PRIN MERIDIAN**: 07

STATE: ND **SURF-ELEV**: 2785.000 **EST-RANK**: lignite **QUARTERS**: SE NE NE NE

COUNTY: Slope **ELVPREC**: **STR-DIP**: **SECTION**: 14

PROVINCE: N Great Plains **THICKNESS**: 660.000 **LATITUDE**: 46-25 **TOWNSHIP**: 134 N

REGION: Fort Union **DESCR-LOG**: **LONGITUDE**: 103-04 **RANGE**: 99 W

FIELD: **WEATHERING**: **LLPREC**:

COMMENT1:

HYDRO CD: **FILEPOINTER**: **OWNERSHIP**:

UNIT DATA

U#	UQ	TK/FT	FORMATION	NAME	priLITH	modLITH	COLOR	grSIZE	grSHAPE
001		24.0			NR				
002		3.0			LIG				
003		1.0			NR				
004		2.0			NR	CARB			
005		185.0			NR				
006		2.0			NR	CARB			
007		1.5			NR				
008		1.5			NR	CARB			
009		1.0			NR				
010		2.5			NR	CARB			
011		89.5			NR				
012		10.5			LIG				
013		52.5			NR				
014		4.0			LIG				
015		280.0			NR				

WILLISTON BASIN MMRRI UNIT RECORD FORM
J.H. Hartman, UND-EERC-MMRRI
data entered on:
printed: 8/7/90

Mno: example REF: ,

LOG TYPE:

STATE: REGION:

===

SECTION THICKNESS in FT: TOP ELEV: BOT ELEV: OUM:

UNIT#: BED NAME: FM:

UNIT THICKNESS in FT: COMMENT:

UNIT THICKNESS CALCULATIONS
DIVISIONS: x + (SCALE:)
METRIC :
PACE & COMPASS - DIP: , DIPrad: , fct: , fctVALUE: , PACE: , SURFACE DISTANCE:

BED DESCRIPTION:

UNIT CHARACTERISTICS
ROCK TYPE: ROCK MODIFIER:
WET COLOR: DRY COLOR:
SEQUENCE: S/S STRUCTURES:
ENVIRON: COMMENT:
Lnos: FOSSIL ENVIRON:
LITHIC-nos:

STRATA/STRATCOL
LITHOLOGY: SYBMOL CODE: WEATHERING PROFILE:

NCRDS FIELDS - UQ:
PRIMARY LITHOLOGY: MODIFIERS: COLOR:
GRAIN SIZE: GRAIN SHAPE: MINERALOGY:
BEDDING: CONTACT: FOSSILS:
FRACTURES: JOINTS: CLEATS:
WILD1: WILD2: COMMENT:

WILLISTON BASIN MMRRI UNIT RECORD FORM

J.H. Hartman, UND-EERC-MMRRI
data entered on: 1988/04/09
printed: 8/7/90

Mno: M0744 **REF:** Van Alstine (1974), No. 1, p. 71-77

LOG TYPE: MS

STATE: ND **REGION:** WB-LMR

==

SECTION THICKNESS in FT: 244.748 **TOP ELEV:** 2844.748 **BOT ELEV:** 2600.000 **OUM:** M

UNIT#: 004 **BED NAME:** **FM:** Slope-JHH

UNIT THICKNESS in FT: 19.357 **COMMENT:**

UNIT THICKNESS CALCULATIONS
DIVISIONS: x + (**SCALE:**)
METRIC : 5.900
PACE & COMPASS - DIP: , **DIPrad:** , **fct:** , **fctVALUE:** , **PACE:** , **SURFACE DISTANCE:**

BED DESCRIPTION: "mudstone; poorly consolidated; dark reddish brown where fresh (moist), light yellowish brown where weathered (dry); blocky on fresh surface; interbedded with less sand; insect parts...single immature gastropod found"

UNIT CHARACTERISTICS
ROCK TYPE: mudstone **ROCK MODIFIER:** blocky, interbedded with less sand
WET COLOR: dark reddish brown **DRY COLOR:** light yellowish brown
SEQUENCE: **S/S STRUCTURES:**
ENVIRON: **COMMENT:**
Lnos: L4962a **FOSSIL ENVIRON:** freshwater
LITHIC-nos:

STRATA/STRATCOL
LITHOLOGY: m **SYBMOL CODE:** SH2 **WEATHERING PROFILE:** 3

NCRDS FIELDS - UQ:
PRIMARY LITHOLOGY: **MODIFIERS:** **COLOR:**
GRAIN SIZE: **GRAIN SHAPE:** **MINERALOGY:**
BEDDING: **CONTACT:** **FOSSILS:**
FRACTURES: **JOINTS:** **CLEATS:**
WILD1: **WILD2:** **COMMENT:**

WILLISTON BASIN FOSSIL LOCALITY FORMS

J.H. Hartman, UND-EERC-MMRRI
data entered on:
printed: 8/7/90

Lno: example REF: ,

FIELD#: REF#: NAME: FOSSILS:

INST: #: #: IN-CHARGE(REF):

==

NAT: REG: FIELD AREA:

STATE: COUNTY: QUAD: YR: SER: CI:

TWP/RGE: sec. , T. ., R. . FSL in ft:

EPOCH: AGE: FM: MBR: M#: U#:

LEVEL: CT: FT/CT: C: ELEV: +/-:
ABV-B: MK: FT/MK: C: SECcode:
BLW-T: MK: FT/MK: C: FSLcode:

ORG FM:
MK COM:

STRAT:

LOC:

COM:

DISC - YR: () by:

FIELD CHIEF: from:
COLL - YR: () by:

COLLN: at:
FAUNAL COM:

IDENTIFICATIONS, identified by:

WILLISTON BASIN FOSSIL LOCALITY FORMS
J.H. Hartman, UND-EERC-MMRRI
data entered on: 1990/04/04
printed: 8/7/90

Lno: L4962a REF: Hartman (1987u off), wkg

FIELD#: REF#: NAME: FOSSILS: N

INST: UND-PC #: A1065 #: IN-CHARGE(REF): Hartman, J.H.

==

NAT: USA REG: WB-LMR FIELD AREA: Cannonball

STATE: ND COUNTY: Slope QUAD: Three V Crossing YR: 1979 SER: 7.5 CI: 20

TWP/RGE: S SW SW sec. 10, T. 135 N., R. 105 W. FSL in ft:

EPOCH: PAL AGE: FM: Slope MBR: M#: M0744 U#: 04

LEVEL: basal	CT:	FT/CT:	C:	ELEV: +/-:
ABV-B: 10.000	MK: T Cross lg	FT/MK: 10.000	C: Ba	SECcode:
BLW-T:	MK: Oyster lg	FT/MK: -86.000	C: 05a	FSLcode:

ORG FM: Ludlow, upper
MK COM:

STRAT: "Mudstone; poorly consolidated; dark reddish brown where fresh (moist), light yellowish brown where weathered (dry); blocky on fresh surface; interbedded with less sand; insect parts (probably contamination) and a single immature gastropod found (A1065)" (Van Alstine, 1974, p. 77).

LOC: Fossil location known from legal location given with measured section.

COM:

DISC - YR: 1972 (07/25) by: Van Alstine, J.B.

FIELD CHIEF: Van Alstine, J.B. from: University of North Dakota
COLL - YR: 1972 (07/25) by: Van Alstine, J.B.

COLLN: Y at: University of North Dakota
FAUNAL COM: freshwater

IDENTIFICATIONS, identified by: Van Alstine, J.B.
gastropod, immature (1)

WILLISTON BASIN FOSSIL SPECIES IDENTIFICATION FORMS

J.H. Hartman, UND-EERC-MMRRI
data entered on:
printed: 8/7/90

Lno: example REFERENCE: ,

STATE: **REG:** **AGE:** **ENVIRON:**

LOCALITY COMMENT:

REPOSITORY: **SPEC#:** **CODE:** **TYPE LOCALITY:**

==

UPDATED IDENTIFICATION

CLASS:
FAMILY: **IDENTIFIER:**

GENUS/SUBGENUS:
SPECIES/SUBSPECIES:

GENUS NOMENCLATURE:
 # SPECIES: **ADDITIONAL COMMENTS** (under wbspcom):
SPECIES COMMENT:

ORIGINAL (or PREVIOUS) IDENTIFICATION

REFERENCE: ,

GENUS/SUBGENUS:
SPECIES/SUBSPECIES:

IDENTIFIER:

WILLISTON BASIN FOSSIL SPECIES IDENTIFICATION FORMS
J.H. Hartman, UND-EERC-MMRRI
data entered on: 1984
printed: 8/7/90

Lno: L0429 **REFERENCE:** Hartman (1984), p. 727-728

STATE: ND **REG:** WB-FTU **AGE:** PAL **ENVIRON:** F

LOCALITY COMMENT: 3 miles below Fort Union

REPOSITORY: USNM-I **SPEC#:** 2,114 **CODE:** **TYPE LOCALITY:** T

==

UPDATED IDENTIFICATION

CLASS: G
FAMILY: Subulinidae **IDENTIFIER:** Hartman, J.H.

GENUS/SUBGENUS: Pseudocolumna
SPECIES/SUBSPECIES: vermicula contraria

GENUS NOMENCLATURE:
 # SPECIES: 1 **ADDITIONAL COMMENTS** (under wbspcom):
SPECIES COMMENT: Originally reported by Meek in Conrad (1866), with inadequate indication. See Pseudocolumna vermicula for synonymies.

ORIGINAL (or PREVIOUS) IDENTIFICATION

REFERENCE: Meek (1876a), p. 557

GENUS/SUBGENUS: Columna
SPECIES/SUBSPECIES: vermicula contraria

IDENTIFIER: Meek, F.B.

4.3 Appendix III

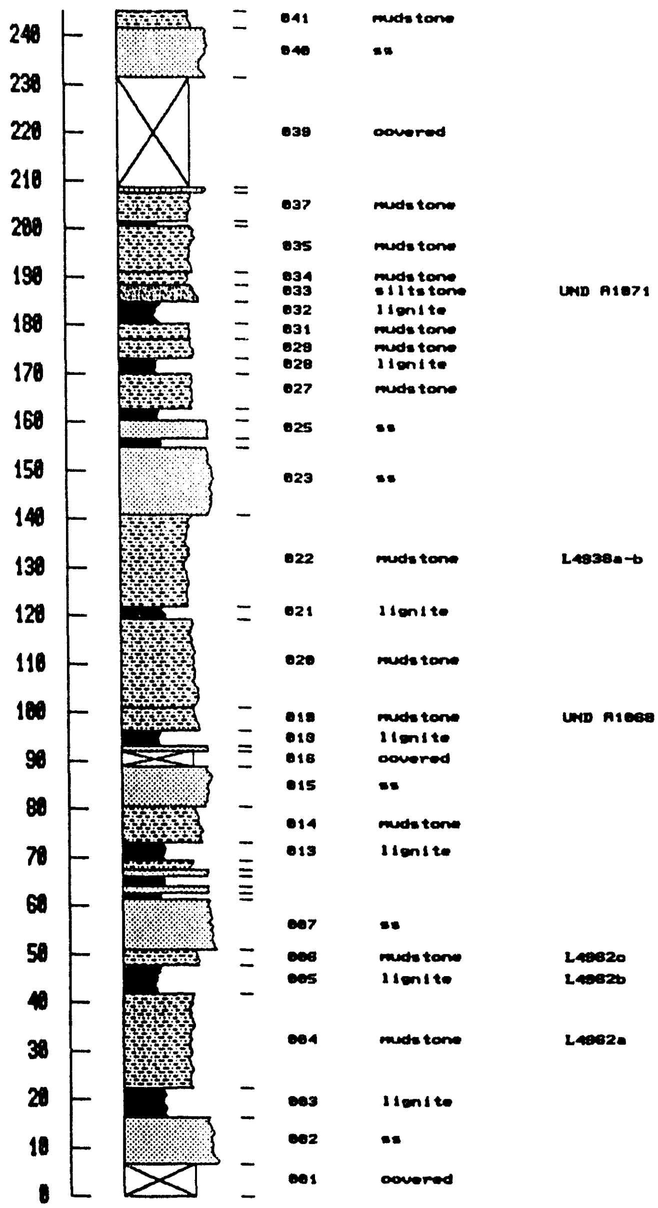
STRATA/STRATCOL Output (Exported Q&A Stratigraphic Data)

4.3.1 Measured *MNOS Section M0744 by Van Alstine (1974) constructed in STRATA/STRATCOL. Primary lithology and locality numbers are displayed in columns to right of unit numbers.

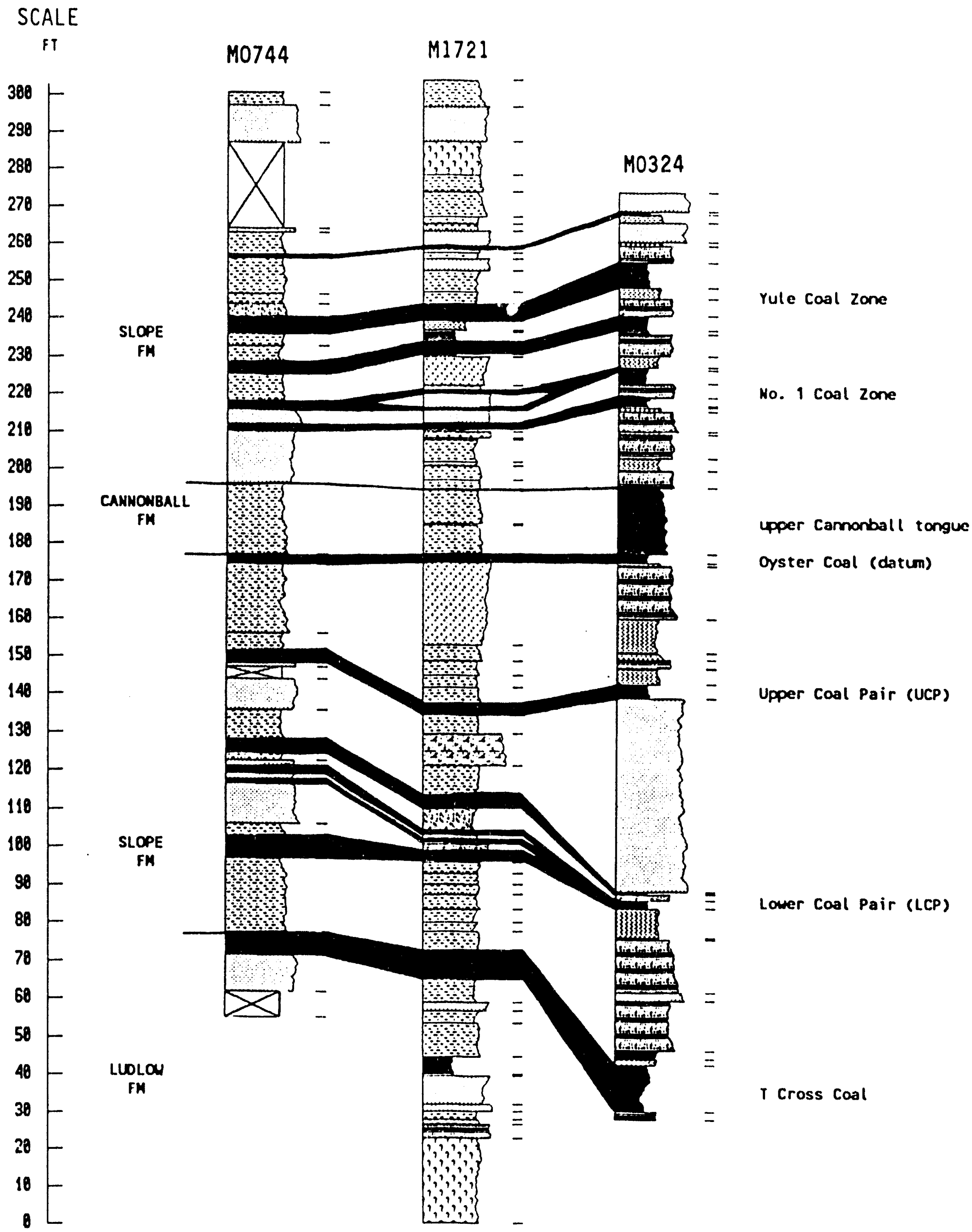
4.3.2 Correlation of measured geologic section in the stratotype area of the Slop Formation, Slope County, North Dakota. Stratigraphic columns contructed and bar scale contructed in STRATA/STRATCOL.

STRAT3 OUTPUT: SECTION M0744

Printed on: 31 July 1990 11:19 am
Scale 1:480
Ticks every 10 ft



CORRELATION OF MEASURED GEOLOGIC SECTIONS IN THE STRATOTYPE AREA OF THE SLOPE FORMATION, SLOPE COUNTY, NORTH DAKOTA



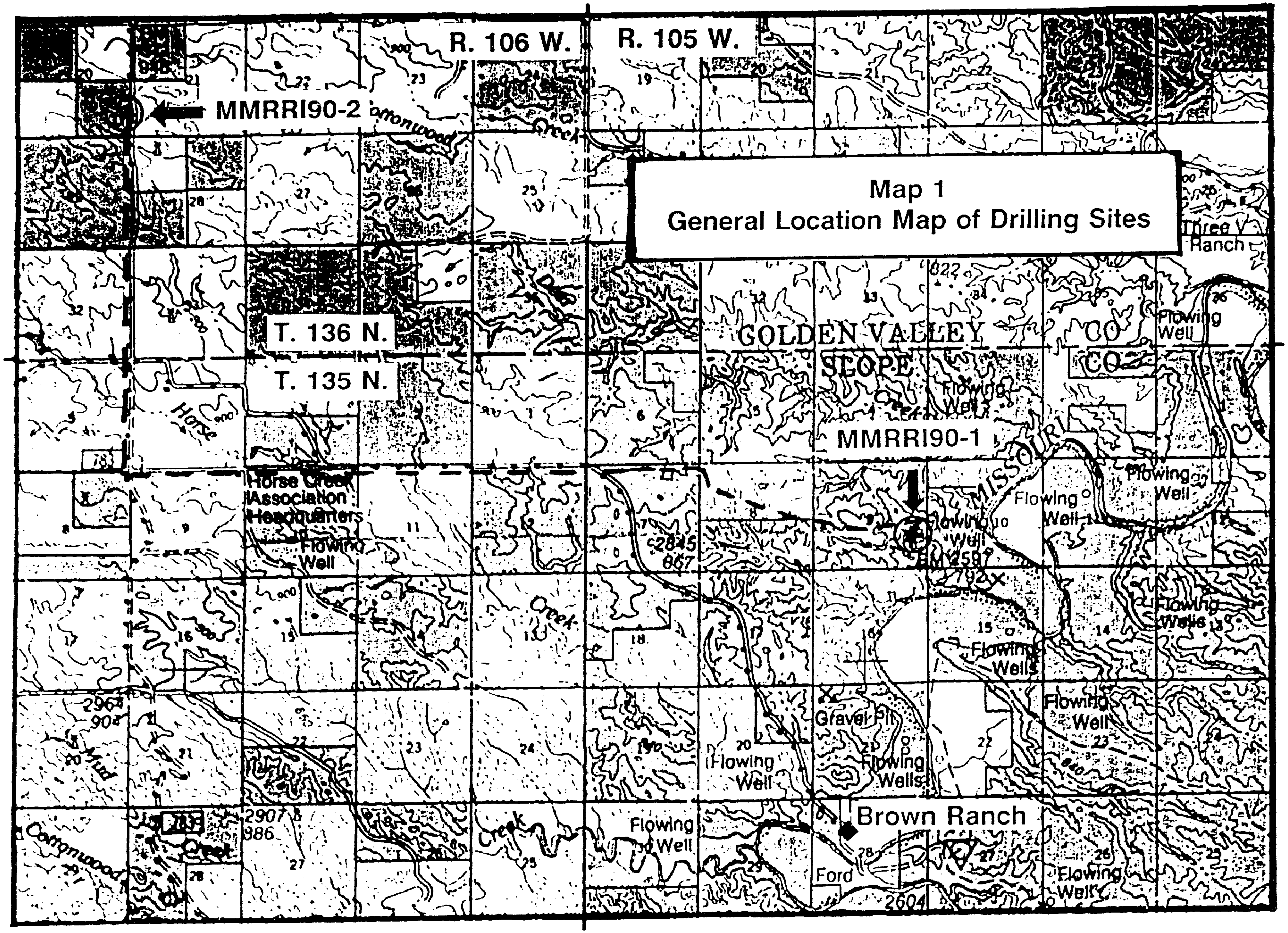
4.4 Appendix IV

Drilling Sites in Western North Dakota

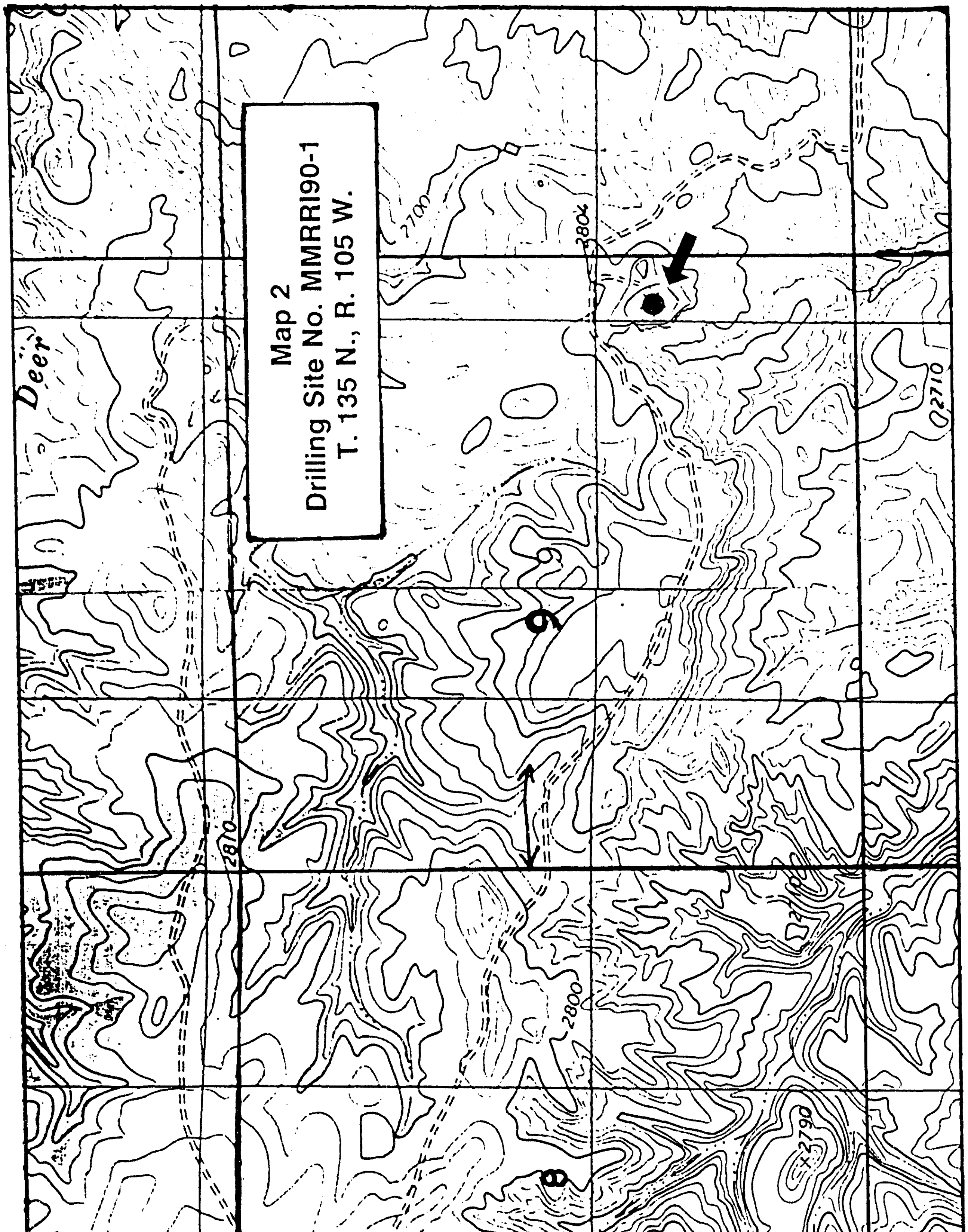
4.4.1 Map 1: General location map of drilling sites (MMRRI90-1, MMRRI90-2)

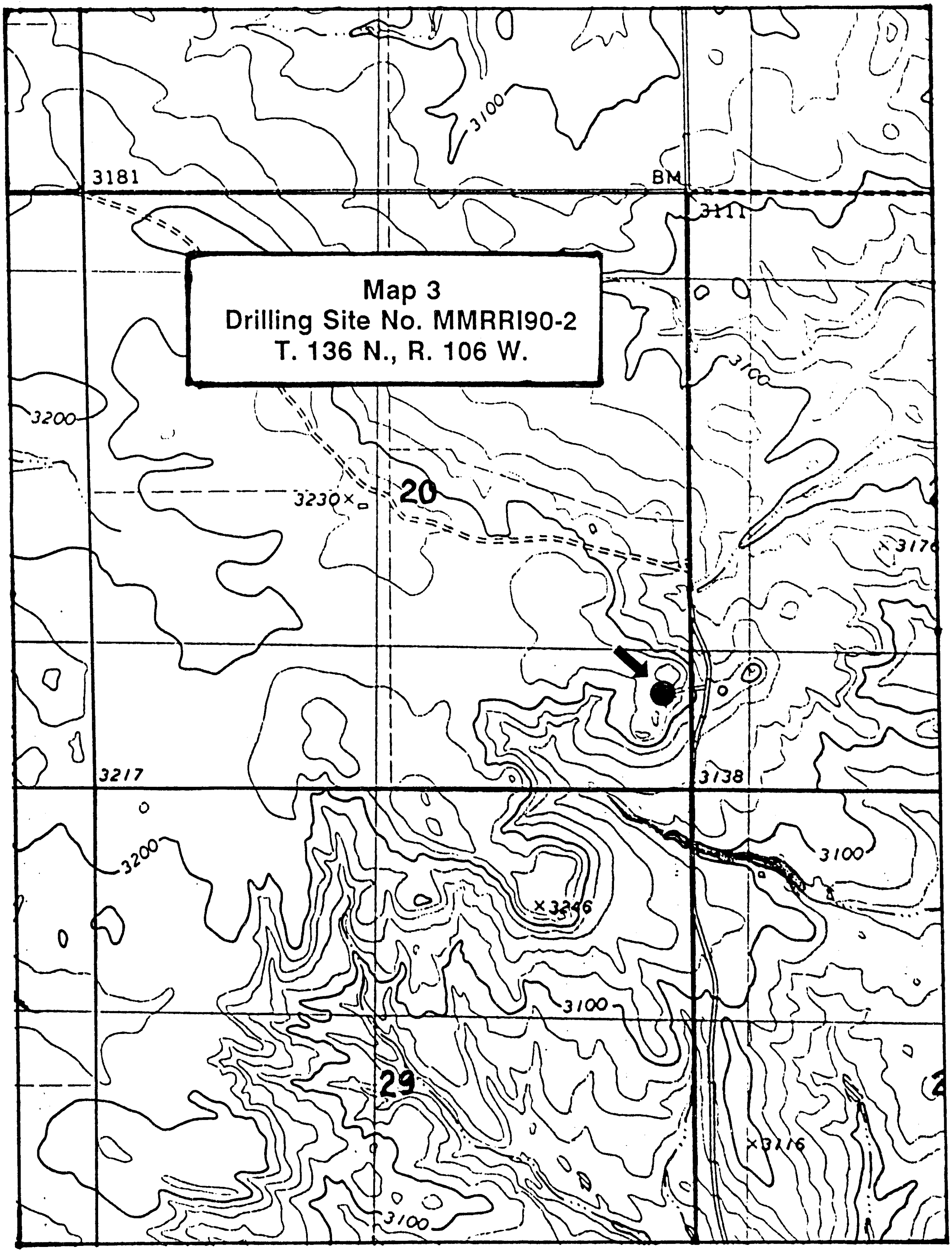
4.4.2 Map 2: Drilling Site No. MMRRI90-1, T. 135 N., R. 105 W.

4.4.3 Map 3: Drilling Site No. MMRRI90-2, T. 136 N., R. 106 W.



Map 1
General Location Map of Drilling Sites


Map 2
Drilling Site No. MMRRI90-1
T. 135 N., R. 105 W.
Deer
2700
2806
2710
2810
2800
2790
9
8



Map 3
Drilling Site No. MMRRI90-2
T. 136 N., R. 106 W.
3181
BM
3111
3100
3200
3230×
20
3217
3138
3200
3100
×3246
3100
29
×3116
3100

4.5 Appendix V

Publications

Kihm, A.J., and Hartman, J.H., 1990, Chronostratigraphic implications of the mammal and nonmarine mollusk record of the Paleocene Fort Union Group in North Dakota: North Dakota Academy of Science, v. 44, p. 70. [accepted; to be presented and published in April].

Hartman, J.H., 1990, Paleocene and lower Eocene nonmarine molluscan biostratigraphy of the Powder River Basin, Wyoming-Montana: Geological Society of America, Rocky Mountain Section, Abstracts with Programs, v. 22, no. 6, p. 14

Hartman, J.H., and Kihm, A.J., 1990, Chronostratigraphy of Paleocene strata in the Williston Basin, in Finkelman, R.B., Daly, D.J., Tewalt, S.J., eds., Geology and Utilization of Fort Union Region lignites [submitted and accepted; to be published in fall 1990].

4.0 COMBUSTION RESEARCH

4.1 Fluidized Bed Combustion

FLUIDIZED-BED COMBUSTION OF LOW-RANK COALS

Annual Technical Project Report
for the Period July 1, 1989 through June 30, 1990

Including

the Quarterly Technical Progress Report
for the Period April through June 1990

by

Michael D. Mann, Research Supervisor
Douglas R. Hajicek, Senior Research Engineer
Ann K. Henderson, Research Engineer
Thomas A. Moe, Research Engineer

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

Contracting Officer's Representative: Dr. Art Hall

for

U.S. Department of Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880

October 1990

Work Performed Under Cooperative Agreement No. DE-FC21-86MC10637

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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 PFBC being 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:

  - Understanding mechanisms involving:
    Mineralogical properties of the bed and coal,
    Fluid mechanics of the bed,
    Corrosion versus erosion, and
    Stress forces on tubes.
  - Assessing acceptable wastages.
  - 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 NSP's Black Dog Station, MDU's 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.

- Scale-up 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 data base has been growing rapidly with all of the new units starting operation; however, much information is still required. The University of North Dakota will have an opportunity to observe scale-up effects for CFBC when the University includes a CFBC as a part of its steam system expansion. This will make a 5,000- and a 150,000-lb steam/hr unit available for scale-up studies.

- 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, conditioning, or other methods should be applied to resolve the problem.

  - Hot-gas cleanup is required for PFBC to meet turbine specifications, in addition to 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 GOALS AND OBJECTIVES

A number of major issues have been identified that warrant further research. EERC has the capability to investigate several issues in atmospheric bubbling FBC. 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 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) fluidized-bed combustion (FBC) program at EERC is to develop a technology data base 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.

2.1 Three-Year Objectives (7/89 - 6/92)

EERC has developed an extensive data base on corrosion and erosion of boiler tubes, agglomeration and sintering of bed material, fuels and sorbent characterization, and particulate emissions through testing funded under the Cooperative Agreement. To successfully transfer this information to the private sector, EERC will continue to publish results from this work at conferences and in refereed journals. The existing data base will be supplemented by low level experimentation, paper studies, economic evaluations, and surveys of operating plants and other researchers' data to fill gaps that may exist.

Pilot-scale work has been performed evaluating the corrosion and erosion of boiler tube surfaces in bubbling beds. EERC has done extensive analysis and characterization of samples generated from this testing. Over the next three years, available samples from industrial and utility-scale boilers will be analyzed and results correlated to bench- and pilot-scale work as well as to each other. EERC will also attempt to obtain funding from non-DOE sources to perform more work on large-scale systems.

Efforts in corrosion and erosion will switch focus to CFBC during this time period. A pilot-scale CFBC is being constructed as a part of another project. Initial work on this unit will involve system, coal, and sorbent characterization. During the characterization testing, an assessment will be made to determine if any meaningful corrosion and/or erosion data can be obtained. If meaningful data can be generated, EERC and METC personnel will discuss the possibility of incorporating CFBC corrosion and erosion work into this program.

Work will continue on the coal pretreatment cell currently being developed at EERC. After each phase of the project, an assessment will be made to determine if the concept is still technically and economically feasible. The end result of this effort is expected to be a design of the pretreatment cell in conjunction with a bubbling and circulating FBC and an economic evaluation of the concept. Testing will be done at the pilot scale, with no demonstration planned as part of this program.

As part of the advanced concepts task and other non-Cooperative Agreement work, EERC will work toward simplifying the control and operation of the FBC. As a part of this task, users of FBC technology will be polled to identify operational problems with fuel and sorbent feed and ash removal systems. Based on priorities identified from this poll and results of other work, EERC will work toward the simplification of control and operation of the FBC. Specific systems will be identified in either the second- or third-year work plans.

First generation PFBC technology has reached commercialization, as indicated by the two recent Clean Coal awards for utility-scale plants. Second generation concepts are now being developed. The success of these concepts will depend, in part, on an understanding of the effects of fuel properties on performance. The EERC will consult with developers of second generation technology on how fuel properties affect drying, pyrolysis, combustion, and topping cycles. The EERC is in the process of designing and constructing a pilot-scale CFBC as a part of a multiclient-funded program. This unit will be used to investigate the impact of CFBC design and coal properties on performance. The test unit would not be available to this program for at least one year. Once the CFBC is available for testing, the current status of the technology will be assessed to determine if and how the unit should be incorporated into this test program.

Atmospheric fluidized-bed combustion has become an acceptable option for the generation of steam and electricity. A number of units are currently on-line in both the industrial and utility sector. Great market potential exists for the use of AFBC technology in both commercial and industrial sectors; however, to increase the acceptability of this technology, low cost, reliability, and ease of operation must be inherent to the system. The purpose of this task is to simplify the control and operation of the FBC for boilers in the range of 10,000 to 200,000 lbs/hr. The goal of this system simplification is to make the unit easier to operate, reduce capital and operating costs, and increase the overall reliability of the system.

2.2 Proposed First-Year Research (7/89 - 6/90)

Specific objectives of the Fluidized-Bed Combustion Project for Year One of this three-year period are as follows:

Task 1. Coal Characterization Reference Guide

To transfer information generated at EERC during the characterization studies, a reference guide will be prepared that discusses the performance, operational, and economic issues related to fuel quality. This guide will rely on information generated at EERC, with supplemental data from other researchers, vendors, and operating facilities. The guide will be directed toward users of FBC technology who need to know the impact of fuel switching on the operation of their unit.

Task 2. Corrosion/Erosion of Boiler Tubes

Samples of boiler tubes and deposits from full-scale units, both industrial and utility, will be obtained. Detailed metallographic analysis will be performed to enable a better understanding of the mechanisms of metal wastage and to extend the data base so that metal wastage between units and coal types can be better correlated. The impact of stress corrosion will also be examined. The success of this task will depend on the availability of samples and the cooperation from FBC users. EERC will also collaborate with Lawrence Livermore Laboratories on sample availability and analysis.

Task 3. Advanced Concepts - Coal Pretreatment Cell

Work will continue on the coal pretreatment cell currently under development at the EERC. Work during the year will focus on pilot testing the pretreatment cell. Information generated during pilot testing will be used to improve the design concept and to generate information for a more detailed economic evaluation of the concept.

Task 4. PFBC Consulting

The EERC will provide consulting services to Foster-Wheeler and MW Kellogg. The focus will be on the effects of fuel properties on the design and performance of their second-generation concepts.

Task 5. System Simplification

The general approach to this work will be, first, to identify the most troublesome, complicated, and costly system components. A second step will evaluate the cost of improving each of the components identified, and the resulting benefits of the said improvement. Based on the cost/benefit analysis, a prioritized list of components for study will be developed. Before any work will begin on the component development phase, the EERC will make recommendations to the METC COTR to obtain approval of the test plan for developmental work. It is anticipated that the developmental work will focus on control systems.

3.0 RESULTS AND DISCUSSION

3.1 Coal Characterization Reference Guide

The planned approach for this task was to supplement data generated at EERC with information obtained from operating facilities to produce a reference guide discussing the implications of fuel flexibility in the FBC. The information generated at EERC has been previously summarized at a recent ASME Joint Power Conference (1) and has been reused in part by *Power Magazine* (2). The supplemental information from FBC users was to be obtained through a survey of their operations. A survey was prepared and sent to approximately 60 operators of bubbling and circulating FBCs. To date, only six of these surveys have been returned. Unless additional completed surveys are received, the information needed to prepare the coal characterization reference guide as planned will not be available.

3.2 Corrosion/Erosion of Boiler Tubes

3.2.1 Corrosion/Erosion/Deposition Topical Report

Systematic studies were performed at 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 as well as 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. Results from this work are published in detail in a topical report (3).

The goal of this work was to identify differences and similarities in materials performance between the different tests. Individual measurements for each metallographic feature taken are presented in this report. 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 will vary from unit to unit, depending upon geometry, operating conditions, and other factors. With this qualification, the general trends observed are shown in Table 1 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 include 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-to-Al_2O_3 weight ratio, and the base-to-acid ratio.

TABLE 1

SUMMARY OF TEST DATA FROM 1000-HOUR CORROSION/EROSION TESTS

	Average Measurements for All Tubes in Category, microns				
Coal Type	Diameter Loss	Wall Loss	Sulfide Penetration	Deposit/ Scale	Diameter Loss + Sulfide Pen
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
Metal Type					
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
Location					
In-Bed	62	163	37	163	99
Splash Zone	77	135	55	91	132
Convective Pass	86	164	15	88	101
Surface Temperature (°F)					
400 (in-bed)	142	237	25	317	167
1100 (in-bed)	56	127	43	104	99
1550 (in-bed)	86	127	54	50	43
250 (convec. pass)	23	96	10	42	33
700 (convec. pass)	47	133	18	115	65
1200 (convec. pass)	196	196	15	105	211

- 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, whereas 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 observed trends were:

  - 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 for the River King test averaged 12 microns.

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

  - 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. Trends were as follows:

  - The largest amount of scale/deposit was observed with the Beulah coal. In this case, deposits as thick as 1/2 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, and Pyro.

  - The carbon steel tubes had almost 3 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 when compared to the splash zone and the convective pass.

  - Analysis of the deposit/scale showed the bulk of the matrix was calcium sodium sulfate-based.

  - The deposit/scale thickness increased with an increase in the sulfur and sodium feed rate and decreased with an increase in the limestone feed rate and the 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 130-MW NSP Black Dog Station when firing coals similar to those used in the EERC tests.

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

- Several coal-related properties affect metal performance. Some of these are measured directly, while others are measured indirectly, such as the composition of the bed materials. 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 increased 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.

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

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

3.2.2 Corrosion/Erosion of Boiler Tubes--Deposit Analyses from MDU Heskett Station

The 80-MW FBC unit at the Montana Dakota Utilities Heskett Station has experienced deposition on both in-bed and convective pass heat transfer surfaces, causing significant reduction in overall heat transfer. The unit is fired with Beulah lignite with a bed material of river sand. Deposits from this unit were collected and analyzed using x-ray fluorescence, x-ray diffraction, scanning electron microscopy (SEM), microprobe, and scanning electron microscopy point count (SEMPC) analyses. The last technique was developed at the EERC specifically to characterize ash-related phenomena. The river sand used as the bed material and a sample of spent bed material were also analyzed by SEMPC. Also, a sample of ash coating from the spent bed material was analyzed. The focus of the analyses was to establish the mechanism of deposit formation and growth. The results of the analyses are as follows.

Table 2 compares the bulk chemical composition of the virgin bed material (river sand), the coal ash chemistry (ASTM ash prepared at 750°C), and the bulk chemical compositions of the in-bed tube and convective pass tubes. Table 3 shows the chemical composition of the samples on an SO_3-free basis. The coal ash was typical of Beulah lignite with high alkali and alkaline earth elements. On an SO_3-free basis, the Na_2O content of the ash was about 8.0 wt%. The virgin bed material was also high in alkaline earth and alkali elements. The spent bed material was surprisingly low in SO_3. This may be due to the high bed turnover rate used at the unit to prevent agglomeration and the high amount of finely dispersed ash which would tend to be elutriated. The Ca/S molar ratio for the spent bed material is 2.44, indicating free Ca available. The spent bed material was also rich in SiO_2 and Al_2O_3. However, the Si/Al molar ratio of the spent bed was much lower than that of the virgin bed (2.73 compared to 4.27). This would indicate a contribution of coal ash material (Si/Al molar ratio for the coal ash is 1.98). Just based on the Si/Al molar ratio, the bed inventory appears to be 35% river sand and 65% coal ash.

The ash coating was rich in SO_3, compared to the spent bed. The Ca/S molar ratio was 2.26, indicating an excess of Ca in the coating. Based on the SO_3-free chemical composition, the ash coating was slightly enriched in Ca and Mg, compared to the coal ash, and very enriched (compared to the spent bed chemistry) in Ca, Mg, and Fe. The Si/Al molar ratio was 1.27, indicating that the aluminosilicate component was formed from kaolinite-derived species (Si/Al molar ratio of about 1) with some quartz.

The two deposits had very high sulfate levels. Indeed, the Ca/S molar ratios for the deposits were less than 1.0, indicating that there was no free Ca in the deposits. The deposits had very similar levels of Si and Al. The Si/Al molar ratios were close to that of the ash coating, indicating that the aluminosilicate material originated from the kaolinite clay with some quartz. The in-bed tube deposit was richer in Ca and Mg compared to the convective

TABLE 2

CHEMICAL ANALYSIS OF SAMPLES FROM THE 80-MW HESKETT STATION (WT%)

Oxides	Beulah Coal	Virgin Bed Material	Spent Bed Material	Bed Material Ash Coating	In-Bed Tube Deposit	Convective Pass Deposit
SiO_2	27.7	61.8	54.3	16.3	6.0	7.6
Al_2O_3	11.9	12.3	16.9	10.9	4.5	5.1
Fe_2O_3	8.3	0.6	2.5	9.9	8.2	28.4
TiO_2	0.7	0.0	0.3	1.0	0.6	0.7
P_2O_5	0.5	0.1	0.1	0.1	1.9	1.1
CaO	17.1	10.2	7.2	28.2	24.7	16.0
MgO	5.5	8.6	2.0	8.6	6.7	3.5
Na_2O	6.3	5.3	7.9	6.2	7.4	10.2
K_2O	0.6	1.0	4.6	0.8	0.4	0.3
SO_3	19.7	0.0	4.2	17.8	39.6	27.0
Total	98.3	99.9	100.0	99.8	100.0	99.9
% Ash	7.3	--	--	--	--	--

TABLE 3

CHEMICAL ANALYSIS OF SAMPLES FROM THE 80-MW HESKETT STATION ON AN SO_3-FREE BASIS (WT%)

Oxides	Beulah Coal	Virgin Bed Material	Spent Bed Material	Bed Material Ash Coating	In-Bed Tube Deposit	Convective Pass Deposit
SiO_2	26.5	61.8	56.7	19.8	9.9	10.4
Al_2O_3	15.6	12.3	17.6	13.3	7.5	7.0
Fe_2O_3	11.4	0.6	2.6	12.0	13.6	38.9
TiO_2	1.3	0.0	0.3	1.2	1.0	1.0
P_2O_5	1.6	0.1	0.1	0.1	3.1	1.5
CaO	27.3	10.2	7.5	34.3	40.9	21.9
MgO	6.5	8.6	2.1	10.5	11.1	4.8
Na_2O	9.6	5.3	8.2	7.5	12.3	14.0
K_2O	0.4	1.0	4.8	1.0	0.7	0.4
SO_3	--	--	--	--	--	--
Total	100.2	99.9	99.9	99.7	100.1	99.9

pass tube deposit. Of interest is that the Na_2O levels for the two deposits were similar. Furthermore, the chemical composition of the ash coating on an SO_3-free basis was similar to the in-bed tube deposit. The notable exceptions were the SiO_2 and Al_2O_3 levels. The convective pass was very rich in Fe_2O_3. The ash coating and in-bed tube deposit had Fe_2O_3 levels similar to the coal ash. Of interest is that as the spent bed was depleted in Fe_2O_3, compared to the coal ash, indicating a large portion of the Fe_2O_3 was elutriated during combustion.

X-ray diffraction analysis was performed on the in-bed tube deposit and the convective pass deposit. The in-bed tube deposit was shown to contain $CaSO_4$ (anhydrite) and hematite (Fe_2O_3). The convective pass tube deposit, however, contained hematite, anhydrite, and glauberite ($Na_2Ca(SO_4)_2$).

The morphology and spatial distribution of the major elements in the deposit samples were determined using SEM and electron microprobe techniques. Each sample in cross section appeared to be a dense matrix with low porosity. Individual fly ash particles were difficult to discern. The matrix material was predominantly calcium sulfate. Examination of the cross sections using backscattered imaging showed that the iron oxide was dispersed through the sulfate matrix as discrete grains. This showed that the iron oxide does not take part in the deposit growth mechanism or contribute to the overall strength. The composition of the matrix material was confirmed by selected point analyses performed using the electron microprobe. The analyses showed that the matrix was almost pure calcium sulfate or sodium calcium sulfate. Some points were almost pure sodium sulfate.

The results of the SEMPC analysis of the various samples are listed in Table 4. The results are listed in terms of volume percent of each of the phases. The virgin bed material contained albite ($NaAlSi_3O_8$), quartz, dolomite ((Ca, Mg) CO_3), illite, and trace amounts of kaolinite and unclassifieds. The unclassified phases are those which don't meet the chemical criteria of the technique. For our purposes, these phases were assumed to be amorphous. The analysis showed that while the virgin bed material had a high sodium composition, the sodium was bound chemically to Si and Al. Furthermore, there was some available sorbent in the form of dolomite in the bed material. The SEMPC analysis of the spent bed material showed that the bed material contained approximately the same amount of albite, but was significantly depleted in quartz. There was some anhydrite observed in the spent bed, along with traces of nepheline ($NaAlSiO_4$), akermanite ($Ca_2MgSi_2O_7$), and anorthite ($CaAl_2Si_2O_8$). The spent bed also contained kaolinite, illite, and montmorillonite, as well as a high level of unclassified (amorphous) material.

The ash coating was shown by SEMPC analysis to be rich in unclassified material, kaolinite, and anhydrite. Nepheline, akermanite, anorthite, and iron oxide were detected. Of significance was the absence of albite, illite, quartz, and dolomite (i.e., the phases in the virgin bed) within the ash coating. Based on this analysis, it appears that the ash coating was formed from the coal ash with no contribution from the bed material.

TABLE 4

SEMPC ANALYSIS OF SAMPLES FROM THE 80-MW HESKETT STATION

	Coal	Virgin Bed Material	Spent Bed Material	Ash Coating	In-Bed Tube Deposit	Tube Deposit Morphology	Convective Pass Deposit
Silicates							
Nepheline	--	--	0.8	4.0	--	--	--
Ankermanite	--	--	0.4	2.0	--	--	--
Gehlenite	--	--	--	--	--	--	1.2
Pyroxene	--	--	--	--	--	--	0.8
Albite	--	32.6	39.9	--	--	--	--
Anorthite	--	--	0.4	2.0	--	--	--
Oxide or Carbonate							
Quartz	x	28.1	7.7	--	--	--	0.4
Iron Oxide	--	--	0.8	4.0	--	x	14.5
Ankerite	--	--	--	--	--	--	0.8
Dolomite	--	28.1	--	--	--	--	--
Sulfate and Sulfide							
Barite	x	--	--	--	--	--	1.2
Anhydrite	x	--	3.7	14.0	--	x	4.1
Sulfated Ankerite	--	--	--	--	--	--	1.2
Sodium Calcium Sulfate	--	--	--	--	35.4	x	12.8
Pyrrhotite	--	--	--	--	--	--	1.2
Pyrite	x	--	--	--	--	--	--
Unclassified or Amorphous							
Unclassified	x	1.1	38.7	64.0	64.6	x	71.5
Kaolinite	x	1.1	4.5	12.0	--	--	0.4
Kaolinite-Derived	--	--	--	--	--	--	0.4
Illite	--	9.0	2.5	--	--	--	0.4
Montmorillonite	--	--	0.8	--	--	--	0.8
Calcium-Derived	--	--	--	--	--	--	--
Amorphous	*						
SiO_2	27.7	NA	NA	NA	9.3	10.2	28.8
Al_2O_3	11.9	NA	NA	NA	7.2	10.5	16.9
Fe_2O_3	8.3	NA	NA	NA	11.6	12.4	25.8
TiO_2	0.7	NA	NA	NA	0.7	1.4	1
P_2O_5	0.5	NA	NA	NA	0	0	0.1
CaO	17.1	NA	NA	NA	36.7	30.9	10.9
MgO	5.5	NA	NA	NA	14.9	14.6	4.6
Na2O	6.3	NA	NA	NA	17.4	14.8	8.7
K_2O	0.6	NA	NA	NA	1.1	1.3	2.3
SO_3	19.7	NA	NA	NA	0	0	0

* Bulk Ash Analysis for Coal
NA Data Not Available
-- Phase not detected
x Phase detected, but not quantified

With respect to the in-bed tube deposit, only sodium calcium sulfate and unclassified phases were observed. The bulk of the unclassifieds were, on further analysis, sulfate phases mixed with other components. The iron oxide was shown by microprobe analysis to be finely dispersed discreet grains too small for spatial resolution by the SEMPC technique. The major phases observed in the convective pass tube deposit were iron oxide, sodium calcium sulfate, and unclassifieds. Some calcium sulfate and gehlenite ($Ca_2Al_2SiO_7$) were observed. Once again the unclassified material was shown to be predominantly rich in calcium and sulfur.

The results of the analysis showed that the Beulah coal ash has a definite propensity for deposition. The formation of ash coating on the surfaces of the bed material is a precursor to agglomeration. It has been shown that the ash coating is derived from the coal ash; in particular, the calcium and sulfur. The deposits, including the ash coating, had chemical compositions very different than the spent bed material. This indicated further that the deposition mechanism was a selective process. In all cases the predominant enrichment was observed with respect to the Ca and S. Significant Fe enrichment was observed in the convective pass tube deposit. However, the Fe did not appear to be responsible for the deposit growth.

The evidence suggested that the cause of the deposit growth was due to the formation and presence of sodium calcium sulfate in the bed. This material was formed from the organically bound sodium and calcium in the Beulah coal reacting with sulfur. There was no free calcium observed in the deposits. The fine-grained sulfate mixture appeared to have an affinity for the cooled surfaces, including the bed particles. Furthermore, there appeared to be a distinct tendency of sulfate species to sinter. The matrix was too fine-grained to establish the presence of a melt phase. It should be noted that sulfate species crystallize readily on cooling. It is suggested that 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 such phases as nepheline, anorthite, and gehlenite would suggest relatively high transient temperatures being reached within the bed. The silicate phases, while showing melting behavior, were not present in significant quantities to have a significant effect on the deposition phenomena.

The deposits formed are very similar to the dense fouling deposits observed with high alkaline earth and alkali fuels in large-scale conventional combustors. These deposits also tend to be predominantly calcium sulfate with the presence of fluxing components such as sodium or potassium. Here, a significant amount of ash component partitioning within the combustor occurs to form an ash stream rich in calcium sulfate. These deposits grow relatively slowly, but are usually dense, hard-bonded, and in areas difficult to sootblow.

The analysis of the pilot-scale data and that from the 80-MW Heskett Station indicate that there is a tendency of certain coal ashes to form deposits in a fluidized-bed combustor. The mechanism of adherence and growth, for the case with the Beulah coal, appears to be via a molten sulfate matrix, due to the fluxing action of sodium with the calcium sulfate matrix. The bed material plays no significant role in the deposition mechanism. The concurrence of the pilot-scale data with data from Heskett Station demonstrates the effect that ash chemistry can have on a fluid-bed system.

3.3 Advanced Concepts and Special Applications

3.3.1 Conceptualization of the Pretreatment Cell

EERC has begun work on developing a new process for an advanced fluidized-bed combustion system. The impetus of this program is 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.

Based on preliminary screening efforts, EERC has focused attention on developing a pretreatment cell to be used in conjunction with any number of combustor designs. The operation and function of the pretreatment cell, as envisioned thus far, is based on previous studies. Details are left out at this time while patentability is being checked. The process, as envisioned, will feed raw coal 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 or severity of these processes can be controlled by varying several operating parameters. These reactions and changes will occur using heat generated from combusting a small portion of the coal, and no external heat source will be required.

The pretreatment cell will be operated as a fluid bed. Velocity and vessel design will be chosen to allow classification of the fuel. Existing data show that an optimal size exists for fuel feed into an FBC, in terms of both top and bottom size. As a result, coal preparation is often a significant operating cost. Data show that size reduction of all coals tested will occur under the conditions planned for the pretreatment cell. Large-sized coal (top size to be determined by testing) can be fed into the pretreatment cell. The vessel will be designed with less surface area on the bottom (high velocity) than at the top of the bed surface (lower velocity) so that segregation will occur. 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 the 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 fuels 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 (4). For the case using the pretreatment cell, data taken from previous work 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 calculations also indicated an optimum 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 an overall 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 cost because of reduced fan requirements.

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 less 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.
- Sorbent utilization may be improved by precalcining the sorbent material before feeding it into the combustor.
- The total plan area of the pretreatment bed, the combustor, and the calciner would 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 size 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.

- 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.

The net result of these benefits is the realization of several of the initial goals defined in the DOE METC Advanced Concept Program. Although none of these have been quantified, the system being developed is expected to result in lower capital and operational costs, higher overall boiler efficiencies, higher utilization of sorbent alkali, lower overall NO_x emissions, higher volumetric heat release rates, a simplified fuel feed system, extended fuel flexibility, and improved turndown. Bench-scale tests are being developed to help quantify these advantages and to further define the process. It is anticipated that a patent will result from this effort.

3.3.2 Experimental Verification

Testing of the pilot-scale coal pretreatment cell and analysis of data were performed. Figure 1 shows a schematic of the pilot-scale unit used for testing to date. In the current configuration, coal is fed via a screw feeder into the coal bed just above the distributor plate. A combination of nitrogen and preheated air is used as the fluidizing medium. The addition of nitrogen is used to control velocity, while air is added at a rate to vary air-to-fuel ratio and allow for close control of combustion within the bed. Flue gas would be used in place of nitrogen in a commercial unit. Treated char flows by gravity from the top of the bed into a barrel. Fine coal particles, moisture and volatile gases from the pretreatment cell are carried out of the system, measured, and combusted in an existing pc-fired furnace.

A total of 30 tests have been performed at gas velocities ranging from 5 to 20 ft/sec. The first 17 test runs were conducted at ambient temperature for shakedown and to establish baseline operating conditions. Due to screw feed problems and fluidizing gas capacity limitations, the top size of coal tested was -3/4 inch. Results of cold flow testing indicate that the fluidized-bed pretreatment cell is a very effective classification device and will allow for the production of a uniform fuel in terms of particle size distribution. Figure 2 is a plot of particle size distribution as a function

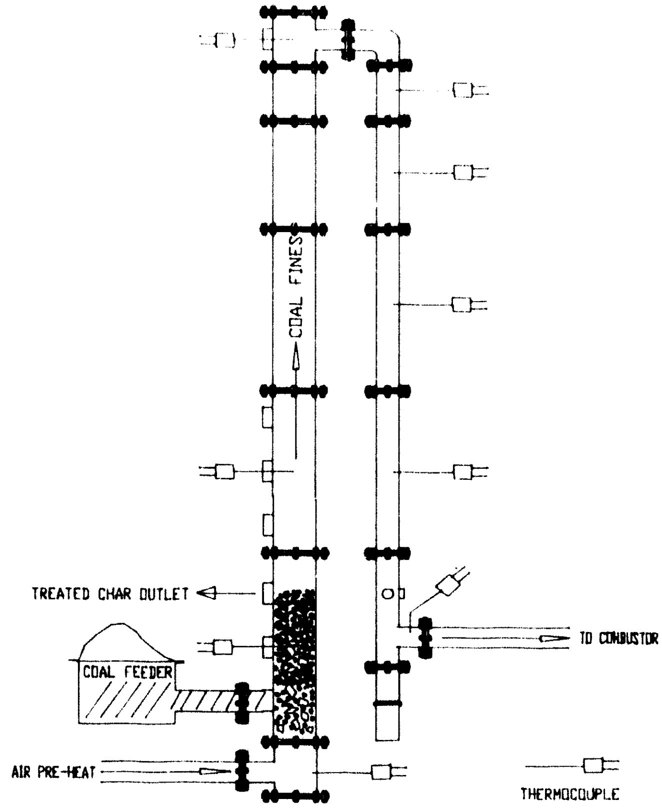


Figure 1. Experimental unit for testing coal pretreatment cell concept.

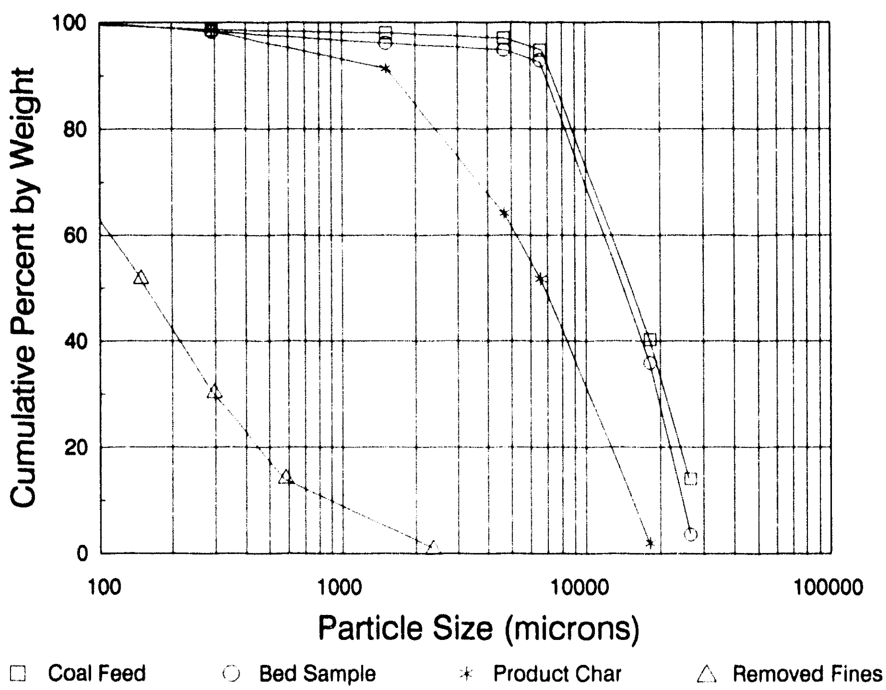


Figure 2. Particle size distribution as a function of product stream for cold model testing.

of product stream. This plot illustrates the variation in particle size distribution between the product char, bed material, and removed fines along with that of the feed coal.

In general, increasing pretreatment cell residence time as a function of coal feed rate results in more effective classification through increased winnowing action of the coal fines. Similarly, increasing gas velocities resulted in greater size separation between the product char and removed coal fines. However, varying residence time as a function of bed height had no apparent effect on particle size distribution of the product char. Additional work is needed in this area to better define the role of bed height on char characteristics.

The cold flow tests were followed by 13 test runs performed at bed temperatures ranging from 100° to 600°F. Initially, -3/4 inch coal was used at bed temperatures ranging from 130° to 210°F and gas velocities of 20 ft/sec to model the lowest section of the pretreatment cell. Additional testing was performed using -1/4 inch coal at much lower gas velocities to simulate the action of the upper portion of the pretreatment cell bed.

Results of the tests using -3/4 inch coal feedstock generally indicate that as bed temperatures increase, degradation of the coal within the pretreatment cell also increases. An illustration of this phenomenon is presented in Figure 3, which shows significant size reduction of the product char with increasing bed temperature. In addition, as the bed temperature was increased from 175° to 210°F, flue gas dust loadings (fines carryover) increased by 50%. Under the same conditions, the moisture content of the flue gas increased from 5% to 10%, while the moisture content of the char product showed reductions of 35% and 59%, respectively, compared to raw coal. Figure 4 shows that increasing bed temperatures result in removal of moisture from the char with a corresponding increase in the ratio of fixed carbon to volatile matter.

Analysis of coal samples taken following each test reveal a concentration of ash at the bottom of the cell. Results from three specific test periods show that 57 wt% of the total coal processed appeared as char, while less than 2% was accounted for in the bed. The balance of approximately 40% was volatiles, moisture, and coal fines carried out of the cell in the flue gas. The ash balance, however, showed 54% of the ash in the char, with 6% of the total in the bed. Additionally, the ash concentration of the material in the bed was as high as 27% on an as-received basis, while the ash in the raw coal was less than 6%, indicating a concentration of ash in the bed. Figure 5 shows the results of proximate analyses performed on the samples from the test periods discussed above.

Results of testing at bed temperatures of up to 600°F suggest increased evolution of volatiles with increasing bed temperatures. Increasing the operating temperature of the bed from 210° to 600°F had no effect on flue gas dust loading, but resulted in an increase in flue gas moisture content of from 10% to 16% due to increased drying of the coal.

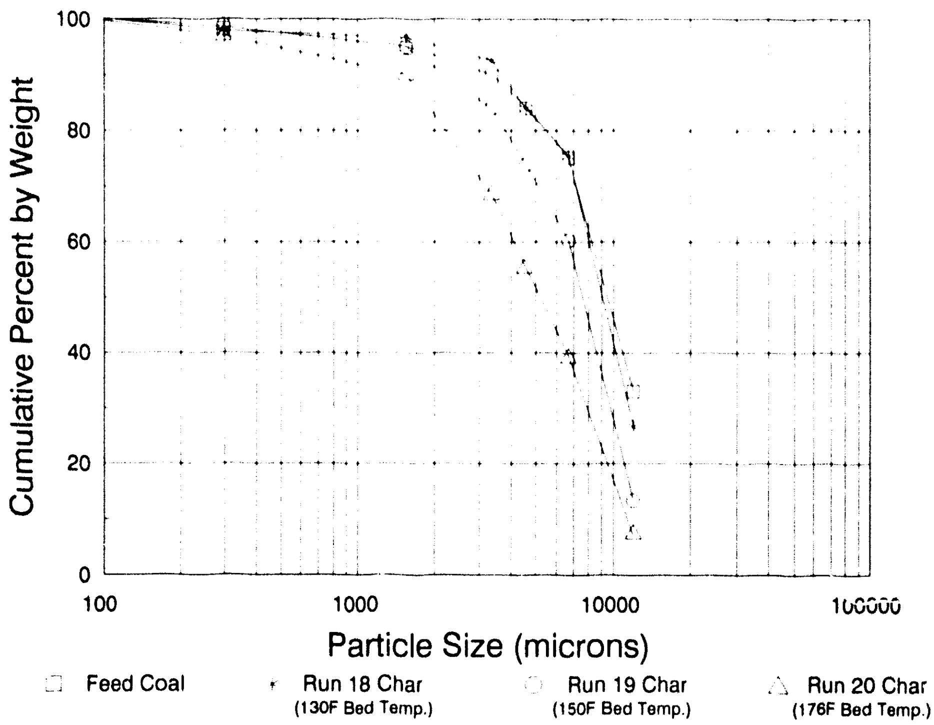


Figure 3. Particle size distribution of char product as a function of operating bed temperature.

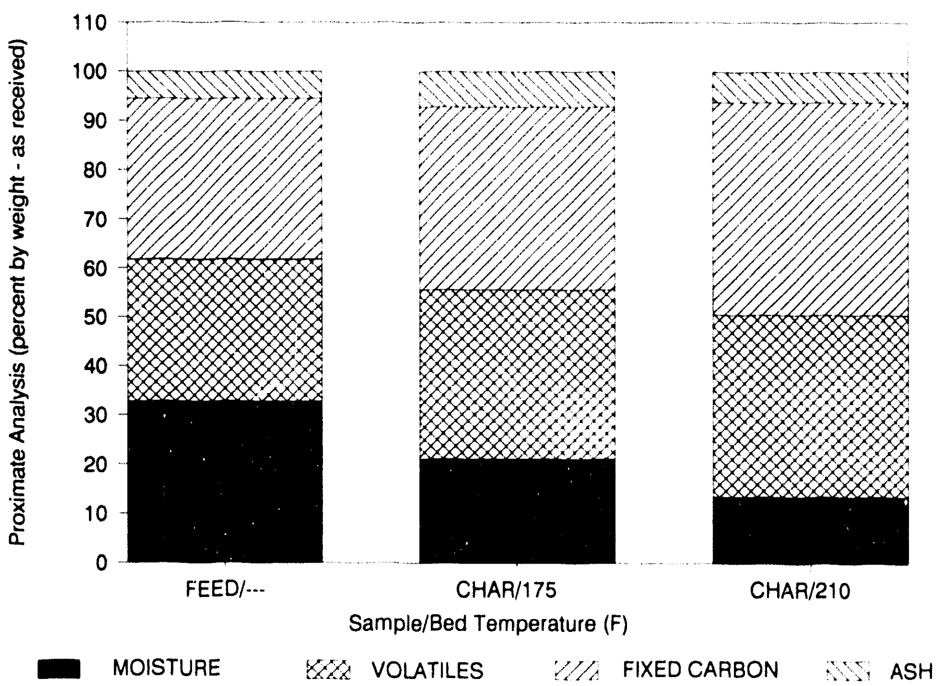


Figure 4. Proximate analysis of char products as a function of temperature.

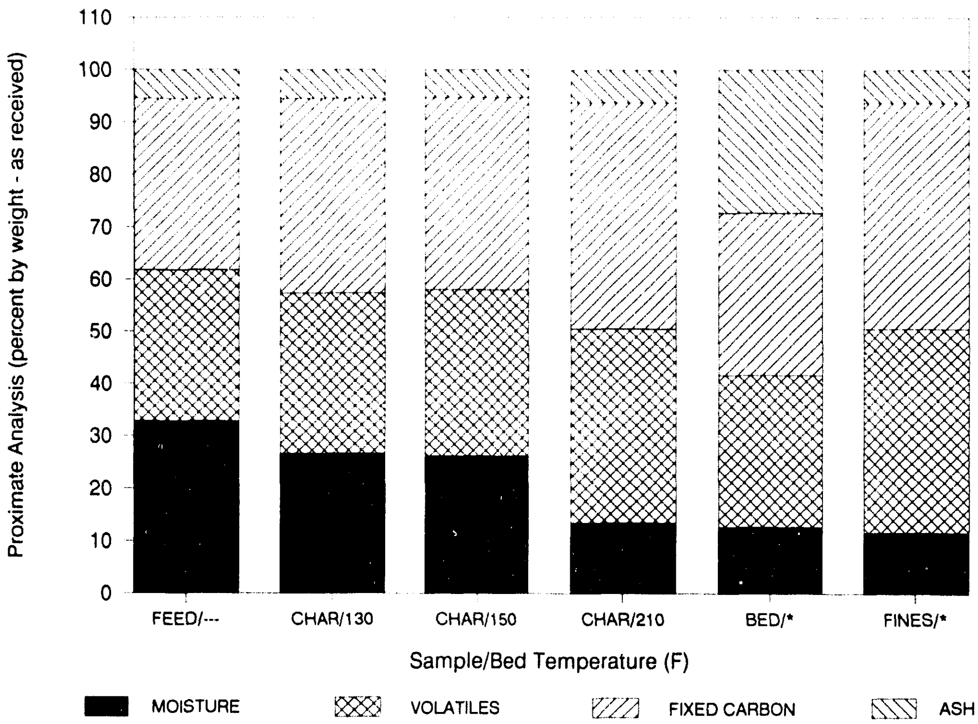


Figure 5. Proximate analysis of product streams from coal pretreatment cell operated at low temperatures. (* = Composite from the three tests at 130°, 150° and 210°F.)

Modifications of the existing pilot-scale equipment have been completed in preparation for the next series of test runs. During the previous high-temperature test runs, it was discovered that excessive heat was being lost through the cell walls, making it difficult to achieve fine control of the bed temperature. Additional insulation was added to the pretreatment cell to cut wall losses to an acceptable level. Modular resistance-type air preheater units have been installed to allow for more close control of inlet air/nitrogen temperatures. A conic bed section installed into the existing pretreatment cell will more closely model the original concept. Also, the point of coal feed has been moved to near the top of the bed to alleviate the problems encountered during earlier runs feeding large particle size material. Testing will be performed at higher operating temperatures and under more controlled air-to-fuel ratios during the next program year.

3.4 PFBC Consulting

A visit was made to Foster Wheeler Development Corporation to discuss ways in which the EERC DOE Cooperative Agreement program could meet the mutual goals of the two organizations. Foster Wheeler is currently working on a second generation PFBC which uses a pyrolysis step to produce a char burned in a circulating PFBC. The flue gas from the PFBC is combined with the low Btu gas from the pyrolysis step and burned in a topping cycle to raise the temperature of the gas going into the turbine. FWDC propose a system efficiency of 45% and a reduction in the cost of electricity by 20%. The preliminary feasibility study was based on data generated at EERC, using the mild gasification entrained carbonizer as the pyrolysis unit. No tests have been done to date at the conditions proposed for the system.

Phase I of the Foster Wheeler program, which was all done on paper, has been completed. Phase II will involve testing each of the separate components to resolve problems and to develop the final design of a 5-MW demo plant. Phase III will involve the demo.

Some of the problem areas identified include hot-gas cleanup, performance of the carbonizer, alkali, and sorbent utilization. Ways in which EERC could contribute technically to these areas were discussed. Since no data is available on operating the carbonizer at conditions proposed for the cycle, any data that EERC could generate on the mild gasification unit would be helpful. Some modifications will be required so that the EERC system can operate at up to 1800°F and 14 atmospheres. Pressure will be sacrificed if both conditions cannot be met. This will take some modification of the EERC mild gasification system. Testing will be done on one common coal to establish the scalability of the data between systems. After that, EERC could tack on additional run time to planned mild gasification runs. This would allow testing in a cost-effective manner and would expand the data base on the number and types of coals tested at the carbonizer conditions.

Discussions were held concerning using a bench-scale reactor to look at kinetics and reactions of alkali release and gettering, sorbent utilization, and N_2O formation. FWDC felt these were all valid and important topics for the development of a second generation PFBC. One point discussed was whether there would be a problem sulfating the CaS from the carbonizer once it was introduced into the PFBC. Data from KRW indicated that a coating formed on the limestone particles, preventing sulfation when introduced into an oxidizing atmosphere. If there is sintering or deadburning occurring, this may limit the utilization of available Ca from the limestone and may make disposal a problem. Therefore, it was agreed that more work needed to be done on sorbent testing.

Information on several subjects generated at EERC under the Cooperative Agreement was requested and sent to FWDC. These subjects included in-bed heat transfer; corrosion, erosion, and deposition in FBC; combustion efficiency versus operating conditions; results from the 1-lb/hr mild gasification unit; SEM capabilities; and high-temperature ceramic bags. EERC will continue dialogue with FWDC as the next year's EERC Cooperative Agreement program plan is developed.

3.5 System Simplification

A review of recent articles was performed to determine what users, vendors, and researchers perceive as problem areas with FBCs. A number of different problem areas were identified. The severity of these problems varied from report to report, sometimes significantly, indicating the problem may be either unit-specific or fuel-specific. It was also noted that many problems were a result of scale-up or design errors and many were corrected during start-up of a particular unit. Some of the findings of this literature review are published here.

3.5.1 Corrosion and Erosion

Corrosion and erosion of boiler tubes was recognized as a problem in FBC early in its development. Extensive studies have been carried out on all levels: bench-, pilot-, demonstration-, and full-scale. Four coals were tested at the TVA 20-MW unit (5). Results seemed to indicate that coal type had an impact on the amount of metal wastage; however, other changes made, such as testing of different tube bundle configurations, may have caused the differences noted. It was observed that cast alloys corroded more than wrought and that weldments showed no evidence of corrosion. Weld protrusions into the bed, however, led to erosion-corrosion of the base metal in one case. Protective coatings were tested at TVA and failed at the sample edges. These coatings may be okay on the tubes. Chromizing and aluminizing increased corrosion resistance, but the part life was limited by the coating thickness.

Other systematic studies performed on pilot-scale rigs indicate that metal wastage is a function of coal properties, bed material chemistry, tube location, tube metallurgy, and tube surface temperature (6,7). The feed rate of sulfur, calcium, and sodium into the combustor with the coal correlated with the metal loss. Although an increasing amount of sulfur in the feed was found to increase the amount of sulfide penetration, the total metal loss decreased. The amount of scale/deposit was found to increase with the amount of sulfur in the feed, with the scale/deposit matrix consisting mainly of sodium calcium sulfate. This protective scale layer appears to be promoted by the presence of CaO (7,8). Other elements, such as silica, were found to be more erosive (6,7). The composition, shape, size, and hardness of the bed material all impact the erosivity of the bed material. These are primarily a function of initial bed material and sorbent type, but are also impacted by the coal ash.

Some excellent reviews of metal wastage have been performed and have identified some common and important factors in corrosion and erosion (9,10). The fluidization regime, more specifically the velocity and particle size, play an important role in the amount of metal wastage. Metal wastage often occurs through exfoliation of corrosion-produced oxide layers by impacting bed materials, exposing fresh surface for corrosion attack. This combination of corrosive and erosive forces accelerates metal wastage. The type and surface temperature of the metal tubes have been identified as significant in metal wastage, and various metal types and coatings have been identified as being superior to others. Irregularities, such as instrument penetration, weld beads, tube bends, etc., have been identified as high erosion areas.

Experience and research in the area of metal wastage is at a stage where methods have been developed to reduce or mitigate the amount of metal wastage in bubbling FBCs. These methods include applying refractory to in-bed tubes and water walls, alonizing in-bed tubes, improving the grid nozzle design, changing the in-bed tube slope, minimizing tube bends, applying mechanical tube protection devices, placing in-bed tubes closer to the distributor plate, and using in-line rather than staggered tube configuration (10,11,12).

Even though various methods of controlling metal wastage are currently being used, cases of unacceptable metal wastage are still reported. In addition, the controlling mechanism is not well understood. A number of different mechanisms have been proposed. These will likely be revised and reworked as additional work is done. One reason for the many different postulated mechanisms is that, although many of the factors that affect metal wastage have been identified, these factors are in a delicate balance. A small change in one or more of the parameters may cause a rapid change in wastage rates. As a result, very different results can be obtained from two units running at what appear to be the same operating conditions.

3.5.2 Ash Recycle

Collecting and recycling fly ash has been demonstrated to improve both sorbent utilization (sulfur retention) and carbon burnout (11,13,14). There exists a limit after which increased recycle does not increase sulfur retention or carbon burnout. Units must be designed with the flexibility to operate within this range. One potential problem, however, is that this range, in terms of lbs/hr of ash, can vary considerably between coals and sorbents. Cost savings are achieved with a properly designed recycle system because less sorbent is required to meet emission standards, there is less spent sorbent to dispose of, and overall boiler efficiency increases. These advantages can be offset by increased capital cost, and also increased operating costs if the ash recycle system is not designed properly or is plagued with problems (13).

Although some early designs had problems with ash recycle systems, the industry as a whole seems to be resolving problem areas (15). As an example, the 160-MW AFBC demonstration plant at TVA's Shawnee Plant reinjects ash by gravity feed through a rotary valve into a vertical column. This acts in conjunction with a "J" valve as a head against the pneumatic transport pressure to the boiler. No problems have been reported with this system at this point (16). Foster Wheeler uses a seal pot at each discharge point. Solids transfer is assisted by air at strategic locations to prevent hold-up in the transport pipe. Reinjection needles are protected from high temperatures by air cooling. This system allows for a continuous reinjection rate limited only by collection rate. The system provides even splitting using few moving parts. This results in minimal maintenance cost, and the lower power consumption reduces operating costs of the system (11).

The information reviewed as a part of this study indicates that although some mechanical problems exist with current ash reinjection systems, these problems are being worked out at the plant during start-up, and new designs are being developed to improve the reliability and associated costs of these systems. One variable that users must remember will affect their particular system is the variability of the fuels being used, especially when compared to the design fuel. The fuel variability can invoke capacity limitations or possible handling problems if the ash characteristics of the new fuel differ significantly from the previous fuel.

3.5.3 Sorbent Utilization

Limestone and dolomite are the typical choices for sorbent in fluidized-bed combustion. Although the chemical reactions involved in sulfur capture are relatively straight forward, choosing a sorbent to obtain optimal performance is not. It is typically not the amount of calcium in the sorbent that determines sulfur-capture capacity, but a number of other properties, including friability, porosity, reactivity, and type and amount of impurities. Researchers have proposed empirical models that predict sulfur capture as a function of sorbent properties; however, these models are often applicable to only a small range of sorbents within the range tested for a particular study.

A systematic study was performed by Babcock & Wilcox under funding from the Empire State Electric Energy Corporation, Consolidated Edison of New York, and EPRI. Testing was performed with two different coals and six different sorbents. Several trends noted were different than predicted based on practical experience. For instance, the higher-calcium limestones showed a lower reactivity and lower alkali utilization than the lower-calcium limestones. Another interesting finding was the increase in NO_x emissions with the higher-sulfur capture capacities of some of the limestones (17). Other researchers have found NO_x emissions to increase with an increase in the Ca/S ratio and when dolomite was used rather than limestone (18,19).

A number of researchers have noted that the properties of the limestone impact performance (17,19,20); however, studies to date fail to accurately quantify these effects. Some work indicates that sorbent utilization increases as the particle size decreases (21,22,23), while other data indicates that, while this is true as particle size decreases from coarse to fine, there is a point where increasing fineness decreases performance (20,23). The effects of sorbent surface area versus elutriation play an important role in this balance.

Dolomite has been used as a sorbent, resulting in a higher utilization of calcium than for limestone sorbents (19,24). Ninety percent sulfur removal was achieved with a Ca/S ratio of 2.1 for dolomite versus 3.4 for limestone in one study when firing a 3% sulfur coal (24). Differences are not as dramatic in other work. Although the utilization of calcium is improved when a dolomitic sorbent is used, it must be remembered that the dolomite contains less calcium than the limestone, and the total amount of material required on a pound-per-pound basis may still be higher for the dolomite.

Coal ash is not an inert material, and will interact with the sorbent. B&W studied this interaction of coal ash on sorbent properties, with interesting results (17). When limestone was calcined and sulfated separately, in the absence of coal ash, the limestone maintained a porous surface. When calcined and sulfated in the presence of coal ash, many of the pours plugged and the limestone had a relatively smooth surface. The surprising result, however, was that better sulfur capture was obtained using the sorbent calcined in the coal ash. Different sulfur capturing capacities were also noted between the same sorbent for two different coals fired under identical conditions.

The importance of limestone properties has also been seen in full-scale plants. During the initial start-up of the Northern States Power Black Dog Station, a number of operating problems were encountered relating to the friability and reactivity of the limestone that was being used as bed material (25). Pilot-scale testing on the EERC pilot-scale bubbling FBC indicated that proper selection of the sorbent material could eliminate many of the bed material problems (26). The use of petroleum coke to increase the rate of sulfation of the limestone was also investigated as a method of stabilizing the bed.

Other examples could be cited to show the importance of limestone on FBC performance. It is important to note that, although a significant amount of work has been performed on bubbling beds, the effects of limestone properties and their interaction with coal type is not yet fully understood. Even less data is available from circulating FBCs.

3.5.4 Fuel Characteristics

Although the fluidized-bed combustor has fuel flexibility as one of its advertised advantages, it has been shown that fuel properties do have a significant effect on the design and operation of an FBC system (27). The same boiler can burn two drastically different fuels, but not necessarily with the same efficiency and output. Given a fixed FBC system, only a limited number of fuels can be burned and still maintain design efficiency. For example, choosing a lower cost, poorer grade coal may offer savings in fuel cost, but costs are offset by greater sorbent usage and higher ash disposal costs. In addition, total system output may be limited by fuel handling and feeding systems or the size of the particulate and ash removal systems (28). For difficult fuels, additional or different start-up systems may be required. Additionally, efficiency losses due to carbon carryover, ash and limestone removal, and moisture varied from 6.7% to 12.8% for one suite of test coals (27,29).

Various researchers have investigated how coal properties affect performance in an effort to develop predictive methods (27-31). It has been determined that standard ASTM methods for characterizing coal do not provide adequate information for prediction of FBC performance. In addition to the standard fuel data, other items such as feedline and feedpoint attrition, devolatilization, swelling, fragmentation, char physics, and combustion-enhanced mechanical attrition need to be characterized (31). Pilot-scale testing is recommended for cases where a new fuel is planned.

In designing an FBC, several guidelines have been suggested in terms of fuel flexibility. All possible fuels and sorbents should be examined before the plant is designed. The extremes in a particular coal supply should be looked at as well as the typical properties, as it is often the extremes that cause the problems. It is important to realize that selection of the best fuel and sorbent are site-specific. Also, there are several ways in which flexibility can be increased, such as the use of solids recycle, staged combustion, and flue gas recirculation. Coal and sorbent feed and ash removal systems must be designed for the worst-case fuel. The end result is that the end user of the system needs to identify how much flexibility he desires, and the cost tradeoffs he is willing to make between capital and operating costs.

3.5.5 N_2O Emissions

Recent studies have identified significant levels of N_2O in the flue gases from fluidized-bed combustors (27,32,33). These levels have ranged from 80 ppm in a full-scale unit at full load, to 315 ppm when operating at 15% to 50% of full load. Tests on a pilot-scale CFBC in Sweden showed concentrations in the range of 80 ppm to 165 ppm. These are significant levels of N_2O and are of a particular concern because N_2O plays an important role both as a "greenhouse" gas and an ozone-layer depleter.

The chemical mechanism of N_2O formation is not well understood. Current information indicates that it is formed at temperatures between 1600° to 2000°F, and that its concentration increases as the temperature decreases within this window. N_2O was seen to increase with increasing excess air and to vary with fuel type. The dependence of fuel type is related to the reactions between NO and nitrogen contained in the char and N_2O formation from char nitrogen during combustion. The one thing that is clear from existing information is that little is understood about this mechanism and what parameters control the formation of N_2O. It is clear, however, that FBC designers and operators must be able to predict and control N_2O formation.

3.5.6 Control Systems

Plant control systems detect and manipulate process parameters. They may be manual (completely run by trained operators), or automated (where some or most of the adjustments are performed by computer). A control system may incorporate an off-line expert system for diagnostics or operator training, or an on-line expert system could be used to augment a process control system by evaluating the data and drawing conclusions.

An expert system is the first practical application of artificial intelligence (35). It consists of a knowledge base, which is a set of rules compiled by human experts, and an inference engine, which assesses information on the basis of the rules to provide a solution. Such a system allows the skills and knowledge of a few experts to be used by a number of operators with less skill and experience (34).

The decision to adopt an expert system may stem from several concerns: fear of losing an expert with specialized skills and experience, inability of an expert to be in more than one place at a time, or difficulty in training engineers to be specialists in more than one discipline (36). Expert systems have numerous applications, including off-line plant diagnostics, off-line operator training, on-line process control, safety studies, and risk analysis (37). Some of these applications are described below.

Troubleshooting and Diagnostics. This could be an on-line system, which analyzes input signals and diagnoses any problems, then alerts the operator to the problem and recommends appropriate action. An off-line system does not receive data directly. When an operator perceives a problem, he enters it into an off-line computer that can diagnose the problem and suggest action, prompting the operator for additional information if necessary. Problems addressed by either of these systems may be caused by a deviation of a process parameter, an instrument malfunction, or a mechanical failure. Obviously, the quality of the information received from the system depends on how exhaustively information was gathered from human experts.

Alarm Management. A process trip may cause a number of alarms to go off in a short period of time. The system should be able to set emergency priorities for the operators.

Process Control. Assuming that an adequate knowledge base can be developed, a computer-controlled system offers the advantages of speed, accuracy, and consistency of response.

Operator Training. Even the most complex control system cannot replace capable, well-trained operators. An off-line expert system can be used with a dynamic simulator to act as a "plant" on which operators can be trained, offering a wide range of conditions.

Some of the advantages of expert systems over human experts are that they provide more uniform application of principles, they do not jump to conclusions, they always attend to details, and they consider all possibilities. On the other hand, expert systems are limited by the fact that they cannot reason broadly, they are limited to a narrow task, they lack common sense, and they cannot reason by analogy or make simplifying assumptions (38).

The approach to fluidized-bed boiler design control for industrial applications is very different from that for utility boilers (39). It must be easy to install and able to run automatically with low energy consumption (39). CFB boilers are not easier to operate than pulverized-coal boilers, but they can run at constant load for long periods of time (40). Such factors as oversized coal particles, a dilute bed, or low bed temperature may result in a high percentage of unburned carbon in the bed; the control system must be able to operate under these conditions, or at least alert the operator that adjustments need to be made (40). A design criteria addresses the technical specifications of the project and resolves control system philosophy issues at the plant level (41). Since the construction of a new plant or even a retrofit may involve a number of contractors working on different systems, it is important to establish control needs early, so that individual control systems can be integrated into a compatible, overall system. The computer system must be appropriately sized for its required tasks; computer overload results in an excess of trips or an inability of the computer to perform all its functions (42).

An important step in the design of a control system is an analysis of available instrumentation. Fluidized-bed combustion systems have unique sensing requirements, such as fast-responding temperature sensors suitable for a hot, corrosive environment, measuring devices for bed level, oxygen level, and clinker formation, solids transport actuators and flow meters for high-temperature use, and on-line monitoring of coal, flue gas, and particulates

(43). Pressure sensors in the combustor must be located in an area of relatively stable pressure, such as at the top of the combustor, and must account for process noise (44). With adequate instrumentation, temperature and flow (through membrane walls) data can be used to determine the instantaneous heat transfer rate as a function of bed height (45).

The primary control variables are feedwater flow, steam flow, desuperheat spray, air flow to the bed(s), limestone feed rate, coal feed rate, and recycle feed rate. Bed temperature and bed height are two variables that are unique to fluidized-bed combustion (46,47).

Another step is determining the control requirements. These may be based on economic operating conditions, such as maximizing heat transfer and combustion efficiencies; regulatory requirements, which may affect bed temperature, gas velocity, recycle rate, and coal-to-sorbent ratio; physical process constraints, and operating objectives such as load swing capability (46).

Many different control philosophies can be found in the literature. The following section describes some different control strategies, as well as some of the factors that make fluidized-bed combustion difficult to control.

One of the most difficult parameters to control is air flow rate, for several reasons. First, combustion air enters the system in many locations, making O_2 content difficult to measure and control, especially with high turndown ratio (e.g., 3:1) (48). Second, variations in coal size, moisture content, and percent of volatiles make it difficult to maintain or calculate the correct amount of excess air (40,48). Air flow control becomes even more difficult in multicell units (43). In some cases, air flow rate is proportional to the fuel feed rate (49); in other cases, the fuel feed rate follows the total air flow rate (50,51), and the primary air flow rate depends on steam pressure (51). Air flows can also be adjusted based on the levels of CO_2 or O_2 in the flue gas (39,49,51). The pressure in the combustion chamber is controlled by varying the I.D. fan inlet damper (36).

The rate of fuel feed is based on steam demand signal, either directly (52), or based on the total air flow rate, which is based on steam demand (50). Limestone feed rate generally follows the fuel feed rate to maintain a constant calcium-to-sulfur ratio (50), but limestone feed may be adjusted to achieve a desired level of SO_2 in the flue gas (45,52).

Care must be taken to avoid high temperatures in the coal feed system. Pressurizing the coal feeder, taking sealing air from the primary air fan, prevents very hot gas from flowing into the coal hopper (48). Carbon monoxide monitors in the upper section of coal silos detect the beginning of spontaneous combustion, which can be averted by CO_2 purging (53), and high temperature in the coal feeder duct should be alarmed (48).

Maximum SO_2 removal is achieved in a narrow temperature window, making uniform bed temperature essential. Bed temperature in a circulating fluidized-bed combustor cannot be adjusted by changing the fuel flow rate, since fuel feed controls the power output (48). Bed temperature can be controlled with solids recirculation (54).

Ammonia can be added to control NO_x, but ammonia slip may be as hazardous as nitrous oxides. Continuous emissions monitoring (CEM) makes it possible to maintain the delicate balance required to minimize both (55).

There are some unique aspects of controlling load in an FBC boiler. FBCs do not respond as quickly as a PC-, gas-, or oil-fired unit (40). Load changes are achieved by exposing more or less of the in-bed tubes, thereby altering the heat transfer surface area (50,51). Bed height may be changed by altering the feed rate of fuel, sorbent, and/or ash recycle (48,49) by draining the bed (49) or by opening or closing the forced draft damper, which changes bed volume (50). Steam temperature can be controlled by spraying feedwater in between the primary and secondary superheaters (55).

Where large and/or rapid changes in fuel heating value occur, main steam header pressure may best be controlled with a "boiler following" system (40); however, "turbine following" is also used to control main steam header pressure in circulating beds (55). In either case, minor variations in steam header pressure are difficult to avoid (40). Drum and feedwater levels are controlled on the basis of demand signal (55); a control loop reads steam flow and anticipates changes in drum level due to load swings (49). To protect the drum and superheaters in the event of a turbine trip, a second source of feedwater to the drum and waterwalls should be provided (39).

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 the control activities, thereby allowing the owners of smaller boilers to operate the boilers with existing personnel. Optimizing the control of the operating parameters should make the FBC easier to operate, reducing operating costs while increasing system reliability.

4.0 REFERENCES

1. Mann, M.D., B.J. Zobeck, and D.R. Hajicek, "Comparison of FBC Performance as a Function of Coal Rank," Presented at the Joint Power Generation Conference, Philadelphia, PA, September 25-29, 1988.

2. Makansi, Jason, "Fuel Type, Preparation Emerge as Critical to FBC Design," Power, January 1990, Vol. 134, No. 1, pp. 41-44.

3. Mann, M.D., D.P. Kalmanovitch, and D.R. Hajicek, "Corrosion, Erosion, and Deposition of AFBC Boiler Tube Surfaces," Topical Report, work performed under DOE Contract DE-FC21-86MC10637, Grand Forks, North Dakota, July 1990.

4. Dunlop, W., "Evaluation of Alternative Steam Generation Designs for Atmospheric Fluidized-Bed Combustion Plants," EPRI CS-5296, July 1987.

5. Sethi, V.K., D.R. Wilson, and R.Q. Vincent, "Materials Performance Test Results From the TVA 20-MW AFBC Pilot Plant," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 2, San Francisco, California, April 30-May 3, 1989, pp. 827-835.

6. Kalmanovitch, D.P., D.R. Hajicek, and M.D. Mann, "The Effects of Coal Ash Properties on FBC Boiler Tube Corrosion, Erosion, and Ash Deposition," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 2, San Francisco, California, April 30-May 3, 1989, pp. 847-856.

7. Levy, A.V., B.Q. Wang, and G.Q. Geng, "Characteristics of Erodent Particles in Fluidized-Bed Combustors," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 2, San Francisco, California, April 30-May 3, 1989, pp. 945-951.

8. Mann, M.D., D.R. Hajicek, A.K. Henderson, D.P. Kalmanovitch, T.A. Moe, G.L. Schelkoph, and S.J. Selle, "Fluidized-Bed Combustion of Low-Rank Coals," Quarterly Technical Progress Report for the Period July-September 1989, Cooperative Agreement No. DE-FC21-86MC0637T3.

9. Witherell, C.E., "Metallurgical Characterization of Wasted Surfaces of In-Bed Carbon Steel Evaporator Tubes," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 2, San Francisco, California, April 30-May 3, 1989, pp. 937-944.

10. Stringer, J., J.F. Stallings, and J.M. Wheeldon, "Wastage in Bubbling Fluidized-Bed Combustors: An Update," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 2, San Francisco, California, April 30-May 3, 1989, pp. 857-862.

11. Abdulally, I.F., and S. Moore, "Design Update of the Foster Wheeler Bubbling Fluidized-Bed Boiler," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 1, San Francisco, California, April 30-May 3, 1989, pp. 99-106.

12. Vincent, R.Q., D.A. Canonico, and J.M. Wheeldon, "An Evaluation Program for Metal Wastage in Fluidized-Bed Combustors," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 2, San Francisco, California, April 30-May 3, 1989, pp. 927-935

13. Saroff, L., M.T. Zitterbart, A.K. Ahart, and H.M. Hooper, "A Relationship Between Solids Recycling and Sulfur Retention in Fluidized-Bed Combustors," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 2, San Francisco, California, April 30-May 3, 1989, pp. 1003-1008.

14. Mann, M.D., D.R. Hajicek, B.J. Zobeck, D.P. Kalmanovitch, R.J. Kadrmas, and N.S. Grewal, "Fluidized-Bed Combustion of Low-Rank Coals," Low-Rank Coal Research, Work performed under DOE Contract DE-FC21-83FE60181, Grand Forks, North Dakota, June 1986.

15. Shang, J.Y., "Research and Development Needs for Fluidized-Bed Combustion," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 1, San Francisco, California, April 30-May 3, 1989, pp. 141-145.

16. Kopetz, E.A., Jr., and W.G. O'Brien, "Start-up and Operating Experience of the 160-MW Atmospheric Fluidized-Bed Combustion Demonstration Plant at Tennessee Valley Authority's Shawnee Fossil Plant," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 2, San Francisco, California, April 30-May 3, 1989, pp. 709-716.

17. Pirkey, J., and M.K. Senary, "Coal/Limestone Screening," EPRI Seminar on Fluidized-Bed Combustion Technology for Utility Applications, Palo Alto, California, May 3-5, 1988.

18. Geisler, O.J., H. Eipper, A.T. Nguyen, and G. Manss, "40-MW FBC Boiler for the Combustion of High-Sulphur Lignite--Demonstration Plant Design and Operational Experience," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 1, San Francisco, California, April 30-May 3, 1989, pp. 121-126.

19. Senary, M.K., and J. Pirkey, "Limestone Characterization for AFBC Applications," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 1, San Francisco, California, April 30-May 3, 1989, pp. 341-350.

20. Zobeck, B.J., M.D. Mann, D.R. Hajicek, and R.J. Kadrmas, "Western U.S. Coal Performance in a Pilot-Scale Fluidized-Bed Combustor," Proc. of the 9th International Conference on Fluidized-Bed Combustion, Boston, Massachusetts, May 1987.

21. Sethi, V.K., A.E. Bland, and G.J. Snell, "AFBC of a Low-Sulfur Bituminous Coal, Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 2, San Francisco, California, April 30-May 3, 1989, pp. 1211-1217.

22. Valk, M., E.A. Bramer, and H.H.J. Tossaint, "Optimal Staged Combustion Conditions in a Fluidized-Bed for Simultaneous Low NO_x and SO_2 Emission Levels, Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 2, San Francisco, California, April 30-May 3, 1989, pp. 995-1001.

23. Basu, P., J. Greenblatt, S. Wu, and D. Briggs, "Effect of Solid Recycle Rate, Bed Density, and Sorbent Size on the Sulphur Capture in a Circulating Fluidized-Bed Combustor," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 2, San Francisco, California, April 30-May 3, 1989, pp. 701-707.

24. Snell, G.J., J.L. Schafer, H.T. Kim, V.K. Sethi, and J.M. Stencel, "Sorbent Testing for AFBC Applications," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 1, San Francisco, California, April 30-May 3, 1989, pp. 351-357.

25. Larra, J., T. Luger, and R. Follett, "An Emissions Compliance Strategy for a Utility Retrofit AFBC Using Precipitators," EPRI Seminar on Fluidized-Bed Combustion Technology for Utility Applications," Palo Alto, California, May 3-5, 1988.

26. Hajicek, D.R., B.J. Zobeck, M.D. Mann, B.G. Miller, R.C. Ellman, S.A. Benson, G.M. Goblirsch, J.L. Cooper, J.L. Guillory, and A.G. Eklund, "Performance of Low-Rank Coal in Atmospheric Fluidized-Bed Combustion," Technical Information Center, U.S. Department of Energy, DOE/FE/60181-1869, July 1985.

27. Makansi, J., "Fuel Type, Preparation Emerge as Critical to FBC Design," Power, Vol. 134, 1990, pp. 41-44.

28. Chandran, R.R., J.N. Duqum, M.A. Perna, D.D. Sutherland, D.R. Rowley, J. Pirkey, and E.M. Petrill, "Ranking Fuels for Utility-Scale AFBC Application," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 1, San Francisco, California, April 30-May 3, 1989, pp. 313-322.

29. Mann, M.D., B.J. Zobeck, and D.R. Hajicek, "Comparison of FBC Performance as a Function of Coal Rank," Power Generation Conference, Philadelphia, Pennsylvania, September 25-29, 1988.

30. Mann, M.D., and D.R. Hajicek, "Fuel Flexibility and the CFBC," Fifth Annual International Pittsburgh Coal Conference, Pittsburgh, Pennsylvania, September 1988.

31. Chandran, R.R., J.N. Duqum, H.C. Jafari, D.R. Rowley, and M.A. Perna, "Characterizing Fuels for Utility-Scale Atmospheric Fluidized-Bed Combustors," Electric Power Research Institute, Palo Alto, California, June 1989.

32. Amand, L.E., and S. Anderson, "Emissions of Nitrous Oxide (N_2O) From Fluidized-Bed Boilers," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 1, San Francisco, California, April 30-May 3, 1989, pp. 49-56.

33. Salam, T.F., S.F. Sibitain, and B.M. Gibbs, "Reduction of NO_x by Staged Combustion Combined With Ammonia Injection in a Fluidized-Bed Combustor: Influence of Fluidizing Velocity and Excess Air Levels," Proc. of the 10th International Conference on Fluidized-Bed Combustion, Vol. 1, San Francisco, California, April 30-May 3, 1989, pp. 69-76.

34. Finn, G.A. and K.F. Reinschmidt, "Expert Systems in Operations and Maintenance," Chemical Engineering, February 1990, pp. 131-136.

35. Daugherty, D.P. and R.M. Felder, "An Expert System for Scheduling Production in a Multipurpose Specialty Chemicals Plant," Plant/Operations Progress, Vol. 9, No. 1, Jan. 1990, pp. 44-49.

36. Armor, A.F., "Expert Systems for Power Plants: The Floodgates are Opening," Power Engineering, July 1989, pp. 29-33.

37. Madhavan, S. and R.A. Kirsten, "Introduction to Expert Systems and Potential Ammonia Plant Applications," Plant/Operating Progress, Vol. 9, No. 1, Jan. 1990, pp. 1-5.

38. Terry, P., "A Layman's Guide to Expert Systems," Power Engineering, Sept. 1989, pp. 52-55.

39. Virr, M.J., "The Control of Industrial Fluidized-Bed Boiler Plants," Proc. of the 1982 Symposium on Instrumentation and Control for Fossil Energy Processes, June 7-9, 1982, Houston, Texas, pp. 509-521.

40. Johnson, G.L., "Tailoring Controls to Accommodate Circulating Fluidized-Bed Boilers," Power, May 1989, pp. 72-73

41. Cunningham, R., C.R. Stewart, and W.K. Triebel, III, "Instrument and Control Design Criteria for Fossil Energy Process Management," Proc. of the 1982 Symposium on Instrumentation and Control for Fossil Energy Processes, June 7-9, 1982, Houston, Texas, pp. 305-317.

42. Boyd, T.J. and C. Gottschalk, "Operating Experience at TVA's 20 MW(e) AFBC Pilot Plant," Proc. of the 7th International Conference on Fluidized-Bed Combustion, Philadelphia, Pennsylvania, October 25-27, 1982, pp. 755-760.

43. Fraize, W.E. and E. Goodwin, "Instrumentation and Controls for Advanced Coal-Utilization Technologies--Requirements, Technology Status, and R&D Needs," Final Technical Report, August 15, 1981, DE-AC22-80PC30085.

44. Kurjatcko, I. and F. Placer, "Distributed Control System for a Circulating Fluidized Bed in a Small Power Plant," Proc. of the 1989 International Conference on Fluidized-Bed Combustion, Vol. 2, San Francisco, California, April 30-May 3, 1989, pp. 1053-1067.

45. Diacierno, J.P. and G. Feher, "CFB Pilot Plant Testing of Coals, Coal Wastes, and Other Fuels--A Comparison of Performance," Proc. of the 1989 International Conference on Fluidized-Bed Combustion, Vol. 2, San Francisco, California, April 30-May 3, 1989, pp. 905-913.

46. Dixon, R.R. and D.J. Dziubakowski, "Control System Requirements for the 20-MW TVA/EPRI Fluid Bed Demonstration Unit," Proc. of the 1982 Symposium on Instrumentation and Control for Fossil Energy Processes, June 7-9, 1982, Houston, Texas, pp. 530-539.

47. Gangaram, G., R.D. Litt, and E.C. Seber, "Process Control of Multi-Solid Fluidized-Bed Combustion," Proc. of the 1982 Symposium on Instrumentation and Control for Fossil Energy Processes, June 7-9, 1982, Houston, Texas, pp. 522-529.

48. Johnson, G.L., "Factors to Consider When Designing Circulating Fluidized Combustion System Controls," PowerGen '88, Orlando, Florida, December 1988.

49. Cwielag, J.S., "Design of Industrial AFBC Boilers in Poland," Proc. of the 1989 International Conference on Fluidized-Bed Combustion, Vol. 2, San Francisco, California, April 30-May 3, 1989, pp. 913-925.

50. VonHippel, C.S. and P. Leighton, "Controlling a Fluidized-Bed Combustion System," Plant Engineering, November 25, 1984, pp. 62-64.

51. Wormser, A.F., "Fluidized-Bed Fuel Burning," Patent # 4,499,857, Patent Date: February 19, 1985.

52. Oakes, E.J., J. Javen, and F. Engstrom, "Start-up and Operating Experience at the Kauttua 22 MWe Cogeneration Circulating Fluidized-Bed Combustion Plant," Proc. of the American Power Conference, Vol. 44, May 1982, pp. 64-68.

53. Comarato, J.R., "Fluidized-Bed Combustion Operating Experience at the Great Lakes Demonstration Plant," Proc. of the 7th International Conference on Fluidized-Bed Combustion, Philadelphia, Pennsylvania, October 25-27, 1982, pp. 139-149.

54. Adams, C., M. Morris, [illegible]nano, and G. Epis, "Full-Load Firing of Coal, Oil, and Gas in a Circ[illegible]g Fluidized-Bed," Proc. of the 1989 International Conference on Fluidized-Bed Combustion, Vol. 1, San Francisco, California, April 30-May 3, 1989, pp. 107-120.

55. Makansi, J., "Move Toward Process Control for CEM Natural But Slow," Power, August 1989, pp. 9-16.