2.3 Regional Energy Policy Program for the Northern Great Plains

REGIONAL ENERGY POLICY PROGRAM FOR THE NORTHERN GREAT PLAINS

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

by

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TABLE OF CONTENTS

LIST OF TABLES

REGIONAL ENERGY POLICY PROGRAM FOR THE NORTHERN GREAT PLAINS

1.0 INTRODUCTION

The United States is the world's leading consumer of energy. The production and consumption of energy vary over the country as a function of climate, the availability of natural resources, economics, and culture. The northern Great Plains region (Montana, Wyoming, North Dakota, and South Dakota) is an area characterized by many similarities in climate, culture, and physiography. With respect to energy, this region:

- Contains significant conventional fossil fuel resources as well as nonconventional energy resources such as oil shale and geothermal.
- Accounts for over 10 percent of domestic hydrocarbon production, a significant portion of domestic coal production by volume (low-rank, low-sulfur coal), and a significant amount of coal-fired electricity.
- Contains significant research capability, particularly with regard to coal-conversion and oil shale technologies, and with respect to the environmental effects of fossil fuel production, conversion, and utilization.
- Is a net exporter of energy and fossil fuel materials.
- Is a significant consumer of fuel and fossil fuel by-products in the agricultural sector.
- Receives significant revenues and economic support from fossil fuel exploration, production, conversion, and transportation industries, as well as from ancillary industries.

The fundamental intent of the federal Energy Policy is to provide enabling and restraining leverage on the market to protect the public interests that would not otherwise be well served. These interests include the protection of human health and the environment, ensuring an uninterrupted energy supply, resource stewardship, and providing for the national security. Since the first energy shock in 1973, response to uncertainty in energy supply, especially for oil, has varied between two extremes: strong government intervention, in response to energy supply crises, or reliance on market forces.

At the state level, responsibility for energy-related issues is typically divided among a number of agencies. Policy functions are divided among economic development, health and the environment, consumer price regulation, and revenue development (sources include severance, sales, and property taxes). Furthermore, state level activities must be coordinated with federal initiatives. The development and maintenance of well-founded energy-related policy at the state or regional level requires basic knowledge in a number of subject areas, including energy resources, production and utilization technologies, markets, the environment, current and developing federal and state initiatives, and local, regional, national, and international trends.

2.0 PROGRAM OBJECTIVES

The goal of this program has been to develop and manage a series of concise reports and databases intended to enhance the development and implementation of energy-related policies in the northern Great Plains region.

Computerized database products are summarized in Table 1, while project reports are summarized in Table 2. The reports are being treated as open-file documents.

3.0 TASKS/ACTIVITIES

3.1 Task A. Development of an Information Management System

Objective

The objective of Task A was to develop an integrated data management system for the storage, organization, and manipulation of data, as well as allowing for varied output including graphics, such as maps, tables, and reports.

Activities under this task included identifying data types and desired product formats; screening candidate software packages and selecting the appropriate software; and, following testing, develop the appropriate data packages. Given the need to foster ready distribution of the computerized data sets, the software selection criteria included:

- User-friendly, with wide usage in the marketplace
- Low cost
- Highly interactive with other software packages
- Personal-computer-based

Following the software selection, activities included tailoring the data management systems to meet the needs of the overall system and developing appropriate formats for data entry and management. In order to minimize costs to the project, software and hardware costs were shared with other projects when possible.

Accomplishments

Computer Data Management System Software

Three types of data were identified: those with a geographic tie, those which consisted of items in a list, and numerical data. The choice of database software was dictated by the character of the data as follows:

- Data sets with a strong geographic component included regulations, resource/reserve estimates, production, facilities, utilization data,

TABLE 1

Summary of Computerized Databases

Name	Task	Software	Description	Records	Remarks
ENERBIB	B.1	Q&A®	The template contains fields for bibliographic citations and key words for energy-related publications and data bases, particularly for the northern Great Plains region. Key references are indicated. Key words expedite sorting by energy sector (coal, oil, gas, electricity, nuclear, biofuels, geothermal, hydroelectric, and oil shale) and subject area (resources/reserves, production, transportation, consumption/marketing, technology, policy, environmental), as well as by area (e.g., state, geologic province, industry/government region).	1500 records	• Records can be sorted on any field
ENERCON	B.2	Q&A®	The template contains fields for names, addresses, key personnel, and descriptions of energy-related organizations. Subsets include state and federal regulatory agencies, lobbyists, energy companies, and select university departments.	1160 records	• Records can be sorted on any field
PLANT	D	Q&A®	Contains information on coal-conversion facilities (coal-fired electrical generating stations; gasification facilities) in the northern Great Plains region. Template contains fields for facility identification (name and address, owner), boiler/gasifier specifications, average load, fuel type and source, flue-gas cleaning, waste types and management, and financial information. Information developed and confirmed through interviews with regulatory and industry personnel.	23 records	• 22 electrical generating plants • 1 gasification facility
MINE	D	Q&A®	Contains information on coal mines in the northern Great Plains region. The template contains fields for mine identification (name, address, owner), production, customers, geology, environmental, and financial information. Information developed and confirmed through interviews with regulatory and industry personnel.	67 records	• Records can be sorted on any field • Unique combination of information fields
NGPCOMP	A	Atlas GIS®	GIS systems are fully relational data management systems that consist of two file formats: geographic and attribute (d-base). The geographic format consists of three basic levels of resolution for the northern Great Plains region: state, state/geologic province, and county. Attribute file templates include fields for resources/reserves, production, facilities, consumption, waste generation, and management. Numerical and statistical products are available from the attribute files alone while maps are produced from the interaction of the geographic and attribute files.		• Attribute files imported from Q&A® and Quattro® Pro • Attribute files developed under Tasks C,D,E • Requires a minimum of: - 486/50; 200 MB for complete system - 386/25; 100 MB for select attribute files

TABLE 2

Summary of Report Products

Title	Task	Description
Status of coal resource assessment in the northern Great Plains	C	Profiles the current state of knowledge and activities with respect to coal resource/reserve information in the northern Great Plains. Focus is on the Fort Union Lignite Region (coal-bearing area of the Williston Basin) and the Powder River Region (coal-bearing strata of the Powder River Basin) which together account for over 95 percent of the coal reserves in the region.
Federal Energy Policy 1970-1990	G	Contains a summary of federal energy policy initiatives during the period 1970-1990 and provides concise profiles of the coal, oil, and gas sectors as they were at the commencement of the National Energy Strategy development process. Includes a chronology of Energy Policy actions and world events.
Coal-conversion by-products management in the North Dakota portion of the Fort Union Lignite Region: A review of the literature	H	Contains a review of the waste types, management practices, and research findings for coal-conversion by-products (fly ash, flue gas desulfurization wastes, bottom ash). Includes maps of waste generation sites and tables highlighting management practices, select research reports, and utilization options.
Surface mining and reclamation in the North Dakota portion of the Fort Union Lignite Region: A review of the literature	H	Contains a review of the environmental effects of mining and reclamation activities. Includes maps of active mines, research sites, abandoned mined lands (AML) and tables highlighting selected research activities and groups.
Oil and gas exploration and production wastes in the northern Great Plains: Occurrence, character, and management	H	Contains an overview of exploration activity, wastes, management practices, and research findings with respect to oil and gas exploration and production wastes (drilling waste, produced water) in the northern Great Plains. Data portrayed on Atlas GIS map products at the county level includes well populations, production (oil, gas, and water) injection wells, and other waste management sites. Tables show management practices and highlight research findings.

environmental data, and demographics. These data sets were assigned to the **NGPCOMP** (northern Great Plains comprehensive) database.

Geographic Information Systems (GIS©) which relate data within a consistent geographic framework are well suited for analysis of these types of data and have the ability to provide numerical and statistical reports as well as map output. GIS was considered to be the software of choice for **NGPCOMP**.

Following a screening phase, Atlas GIS© was chosen as the software for **NGPCOMP**. The development of **NGPCOMP** was initially delayed, however, due to problems with the generation of the Atlas GIS© software originally obtained for testing. In Year 2 of the project, plans were made to replace Atlas GIS© with MapViewer®, a thematic mapping package from Golden Software. The acquisition of an Atlas GIS© upgrade and the hiring of a full-time computer database manager, both in Year 3 of the project, cleared the way for the development of **NGPCOMP** using Atlas GIS©. Since the formats and files can be readily revised and the program readily accepts information from other database formats, the choice of Atlas GIS for **NGPCOMP** resulted in the potential for a flexible, dynamic, portable, and expandable data management system.

GIS systems, fully relational data management systems, function with the interaction of two file formats--geographic (a standardized geographic reference structure) and attribute (d-base files, akin to spreadsheets, which are keyed to locations in the geographic structure)--where data are tied to a geographic location. Atlas GIS© database construction was initiated with the development of an overall geographic structure for the northern Great Plains region. The geographic structure contained three layers, that of the state, geologic province/state, and county. The county, a geographic unit common among the diverse data sets (regulatory, geologic, production, consumption, environmental), was chosen as the fundamental geographic tie (level of resolution) for the GIS system and proved particularly useful for portraying the occurrence and distribution of elements of the larger attribute data sets such as oil and gas wells. In cases where populations were relatively small, such as the case for coal mines, the capability existed for individual facilities to be plotted while other types of data, including regulations, required plotting at the state or state/province level.

In the second half of Year 3, natural gas-related data were used as the basis for attribute files which were then used as sample data sets for the testing of Atlas GIS© capabilities. With the successful demonstration of the system, subsequent activities included the development of data entry attribute formats, entry of selected data sets, and the production of select map products. Data entry was facilitated by creating attribute file templates in Atlas GIS©, exporting the templates to Quattro® Pro for data entry, and then returning the completed files to the GIS system. Data intended to form the basis of attribute records in **NGPCOMP** were acquired under Tasks C, D, and E. The status of those activities is addressed under the individual tasks.

- Enumerated items and supporting information, which included bibliographic citations, contacts, descriptions of technologies, and policy initiatives, were managed using Q&A®, a flat file manager. Q&A® proved especially useful due to its powerful sorting capability.

- Most of the GIS databases were supported by data sets in a spreadsheet format, particularly Quattro® Pro. This was done for two reasons. The spreadsheet format allowed the rapid input of data and the program embodied powerful statistical and other analytical capabilities.

- Word processing was handled using WordPerfect®.

Computer Hardware

The software packages selected for the project, particularly Atlas GIS©, required improved PC capability. Ancillary capability was required to ensure appropriate products. Costs were shared with other contracts where appropriate. Hardware acquisitions included the following:

- IBM PC 386 SX; 40 MB hard disk; 8 MB RAM

- Upgrades of two IBM PC machines, including hard disk upgrades

- Purchase of a modem for access to on-line information sources

- Deskjet (ink jet printer) printer, produces map products for the Atlas GIS© **NGPCOMP** database.

3.2 Task B. Information Acquisition

The overall objective of this task was to identify information sources with respect to the selected energy-related subject areas in the northern Great Plains and to characterize and assess these sources. Activities fell into two areas: compilation of an annotated bibliography of publications (B.1) and a compilation of background information on key energy-related contacts (B.2).

3.2.1 Subtask B.1 Annotated Bibliography of Energy-Related Sources

Objective

The objective of Subtask B.1 was to identify information materials, published sources, and databases; to acquire and review these materials; and, finally, to enter and manage these materials in a computerized annotated bibliography template developed using Q&A® software. Sources of the materials included trade and lobbying groups, energy-related companies, and state and legislative agencies.

Although the initial intent of this task was to produce an annotated bibliography, the formal review and description of each reference was deemed inappropriate since 1) the activity was time-intensive, requiring an inordinate share of limited project resources; 2) the volume of materials was very large; and 3) annotations were already available in other formats in many cases (such as on-line databases). Instead, the original intent of the annotated bibliography, that is, the ranking and description of the information sources, was largely fulfilled through the identification of key data sources in select subject areas.

Accomplishments

- The identification and acquisition of energy-related sources for the northern Great Plains. Sources included computerized data bases, published materials, and on-line databases.

  - Development of a computer-based annotated bibliography template, **ENERBIB**, in Q&A®. Fields include bibliographic information, key words, and descriptive information.

- Identification of key references by energy sector (coal, oil, gas, electricity, nuclear, biofuels, geothermal, hydropower, oil shale).

3.2.2 Subtask B.2 Organizations Database

Objective

The objective of Subtask B.2 was to identify key energy-related organizations for the northern Great Plains and to develop a computerized data system for the storage and manipulation of these data.

Accomplishments

- Selected energy-related groups at the national and regional levels were identified and contacted during Years 1 and 2 with respect to their activities in policy issues. The groups included environmental organizations, research organizations, government agencies, and industry trade groups.

- Development of the **ENERCON** database template in Q&A® for the storage and management of these data.

3.3 Task C. Energy Resource Database

Objective

The objective of Task C was to acquire data on the energy-related resources of the region and to determine the status of resource assessment.

Accomplishments

- Identifying and acquiring data sources, mainly published reports. These data were prepared for entry into the resource/reserve portion of the **NGPCOMP** database.

  - Information was acquired for coal, oil, gas, nuclear, oil shale, and geothermal. Attribute sets were filled in for coal, oil, and gas.

- Preparation of the report entitled "Status of Coal Resource Assessment in the Northern Great Plains." The report focuses on the status of resource and reserve assessment in the Williston and Powder River Basins which account for over 95 percent of the coal reserves of the northern Great Plains.

  Information on the status of oil, gas, and geothermal resource/reserve estimated were obtained but were not formalized in a report format.

3.4 Task D. Energy Production Database

Objective

The objective of Task D is to develop a computerized database to provide information on current energy-related production. Related databases were planned to pertain to the storage, treatment, and conversion (i.e., mines, power facilities, refineries, gas processing facilities) of fossil fuels.

Accomplishments

- Identifying data sources and obtaining production information from the states and other appropriate groups.

- Development of format and entry of the data into the production portion of the **NGPCOMP** database.

- Development of databases on coal-related production and utilization facilities. These databases served as the source of data in these subject areas for the Atlas GIS© **NGPCOMP** database.

  - Coal Mines (**MINE**)

    MINE is a Q&A® software template which contains information on coal mines within the northern Great Plains region. Each coal mine has an individual entry consisting of background information production figures and customer data as well as geologic, environmental, and financial information. Sixty-seven mines are listrd in the four-state area, including twenty-one operations which are closed temporarily or permanently or have been absorbed into another mine or company.

  - Coal Conversion facilities (**PLANT**)

    PLANT is a Q&A® software template which contains information on coal-conversion facilities (coal-fired generating stations, coal gasification facilities) in the northern Great Plains region. Each coal-conversion facility has entries consisting of background information, boiler/gasifier specifications, average load data, fuel, FGC, waste management, and financial information. Twenty-three entries are included in the four-state region (22 electrical generating stations and 1 gasification facility).

  - Information on other facilities, including gas processing plants and refineries, was not formalized in a database format since it exists in a number of commercially available formats as noted in the **ENERBIB** database. Further, waste and waste management information for these facilities was not readily available.

3.5 Task E. Energy Consumption Database

Objective

The objective is to develop a computerized database to provide information on energy consumption in the region.

Accomplishments

- Data source identification and data acquisition.
- Development of a database format for the **NGPCOMP** database.
  - Consumption-related information was not reduced and entered into the **NGPCOMP** data, since it is already available in a number of formats, including state and federal publications, as noted in the **ENERBIB** database.

3.6 Task F. Energy Technology Database

Objective

The objective is to develop a computerized database to provide information on energy conversion and related technologies, focused on low-rank coal in the northern Great Plains.

Accomplishments

- Preparation of **TECH**, a database template in Q&A® which contains critiques of low-rank coal conversion technologies based on published and in-house sources.

3.7 Task G. Government Initiatives Database

Objective

The objective was to develop computerized databases and supporting documentation dealing with energy-related policy initiatives at the federal and state levels.

Accomplishments

- The compilation of a concise history of energy-related events and policy initiatives during the period 1970 through 1990 at the international, national, and regional levels. Information regarding activities at the federal level is contained in the report "Federal Energy Policy 1970-1990."
- The identification and, where possible, assessment of past federal and state policy actions in a historical context. An assessment of

federal actions for the period 1970-1990 were originally included in a Q&A® database format but this information has subsequently either been included in the report "Federal Energy Policy 1970-1990" or, alternatively, was found to be readily available in more detailed form in on-line formats and publications as indicated in **ENERBIB**.

- Identification and tracking of current policy initiatives, and, where available, acquiring supporting documentation at the federal and state levels. Data sources included:

  - Offices of federal and state legislators and agencies, including USDOE.

  - Industry associations and environmental groups.

  - Legislative tracking groups, notably the Environmental and Energy Study Institute (Weekly Bulletin, Legislation Briefing Books, Special Reports).

- Investigation of the use of on-line policy-related information sources. On-line services were available from the states as well as on the national level from such services as **LEXIS/NEXIS** and **WESTLAW**. However, the cost of the services was prohibitive, and it was decided that state sources would be sufficient for the needs of the program.

  - Database products for legislation at the federal and state level were deemed inappropriate as originally envisioned. Needs in these areas are adequately met by published reports and on-line data services available as indicated in **ENERBIB**.

3.8 Task H. Environmental Issues Database

Objective

The objective was to prepare summary reports dealing with energy-related environmental issues in the northern Great Plains region.

Accomplishments

Reports were prepared to provide background information concerning the environmental aspects of the surface mining of coal, the management of coal-conversion by-products, the management of oil and gas exploration and production wastes, and the ramifications of the 1990 Clean Air Act on coal in the region. The reports are summarized as follows:

- "Surface Mining and Reclamation in the Fort Union Lignite Region: A Review of the Literature"

  - A review of the literature concerning mining and reclamation in the coal-bearing area of the Williston Basin. The paper contains information on abandoned mine land sites, active mining and reclamation sites, and mine land research sites; a review of published reports and research programs; and a statement of research needs.

- "Coal-Conversion By-Products Management in the Fort Union Lignite Region: A Review of the Literature"

  - A review of the literature concerning the management of coal-conversion wastes (fly ash, FGD waste, gasification waste) in the coal-bearing area of the Williston Basin. The paper contains information on waste types and their character, a review of published reports and research programs, management strategies for disposal and utilization, and a statement of research needs.

- "Oil and Gas Exploration and Production Wastes in the Northern Great Plains: Occurrence, Character, and Management"

  - A summary of the oil and gas exploration and production waste (produced water and drilling wastes) generation and management picture by county in the northern Great Plains. The paper contains information on waste character, generation sites, estimated volumes, management practices (allowed and actual), and research projects.

- The decision was made not to prepare two planned documents, "The Clean Air Act in the Northern Great Plains" and "Leasing Federal Lands in the Northern Great Plains: Energy-related Issues," due to the fact that such reports would be premature. In the case of the Clean Air Act Amendments, for example, activities are ongoing in such key areas as the NO_x and air toxics standards.

4.0 TRIPS/INFORMATION DISSEMINATION

- October 1-4, 1989; Rocky Mountain Section Meeting of the American Association of Petroleum Geologists. Of particular interest were sessions on the outlook for the domestic uranium industry, reservoir heterogeneity and the potential for enhanced oil recovery, and oil and gas resources in the northern Great Plains.

- November 6-7, 1989; travel to Washington DC. Activities included a visit to the Energy Information Administration and attendance at a meeting of the DOE-sponsored Coal Awareness Steering Committee.

- January 22-24, 1990; travel to Washington DC. Activities included a visit to the DOE Office of Policy, Planning, and Analysis (OPPA) for discussions with Ms. Sandy Glatt and Mr. Henry Kelly on the form and status of the National Energy Strategy (NES) and examination of the draft NES and testimony from the NES public hearings.

- September 11, 1990; attendance at the Pittsburgh Coal Conference, Pittsburgh, Pennsylvania. Of particular interest were presentations by industry and government representatives in a formal session on the developing National Energy Strategy.

- September 12-13, 1990; attendance at the First International Symposium on Oil and Gas Exploration and Production Waste Management Practices in New Orleans, Louisiana. The conference provided information on environmental issues for the oil and gas industry, including NORM, air quality, and general presentations on exploration and production wastes and waste management.

- September 30, 1991; attendance at a Geographic Information System (GIS) workshop at Argonne National Laboratory, Chicago, Illinois.

Travel was typically undertaken in conjunction with other contracts, where possible, to minimize expenses.

Reports prepared using information developed through this project include:

Energy and Environmental Research Center Technical Staff, 1990, An analysis of energy policy and recommendations: Internal report, 22 p.

Groenewold, G.H., Beaver, F.W., Butler, R.D., Daly, D.J., and Schroeder, S.A., 1992, Overview of mine land reclamation research in the North Dakota portion of the Fort Union Lignite Region: *in* Finkelman, R.B., Tewalt, S.J., and Daly, D.J., eds., Geology and utilization of Fort Union lignites.

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2.4 Hot-Gas Cleanup

HOT-GAS CLEANUP

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

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

HOT-GAS CLEANUP

1.0 INTRODUCTION

The U.S. Department of Energy (DOE) is promoting the development of coal-based advanced power systems under the direction of Morgantown Energy Technology Center (METC). This activity covers a broad range of technologies involving combustion, gasification, and the integration of combustion and gasification technologies. The objective is to maximize cycle efficiencies to provide for a stable, secure, and environmentally sound energy future.

Specific combustion program areas include the development of heat engines, such as direct coal-fired turbines and diesels and pressurized fluidized-bed combustion (PFBC). Gasification technology development includes mild gasification for coproducts and hydrogen and methane production for fuel cell applications. Integrated gasification combined cycle (IGCC) technology promotes high cycle efficiencies by combining coal gasification with direct product-gas firing in turbines. In all of these cases, hot-gas cleanup systems are required to achieve acceptable process performance and to meet current and future environmental emission standards.

The Energy and Environmental Research Center (EERC) is currently involved in a number of research projects in both the combustion and gasification of coal and also in gas-stream cleanup. The fundamental gas-stream cleanup issues common to the various advanced concept systems are being investigated in this project. Emphasis is being placed on particulate control techniques and on ash/alkali interactions with the filter materials.

The Center has been involved in research related to ash/alkali interactions and slag behavior for many years. This expertise is being used in studying the effects of alkali interactions with filter media and possible mitigation options that may improve filter life. The global or overall objective in this phase of the project is the study of the thermodynamically equilibrated reaction mechanisms and mineral matter transformations in advanced coal combustion systems.

2.0 GOALS AND OBJECTIVES

The goals of the hot-gas cleanup project at the EERC are to build and operate a hot-gas cleanup test loop in conjunction with various pilot-scale advanced systems currently in operation at the Center, to explore the various ash/alkali corrosion mechanisms for ceramic barrier filter materials, and to determine the effects of various mitigation options. The mitigation options will focus primarily on gettering techniques. Eventually these techniques will be verified at the pilot scale using the hot-gas test loop.

The Center is currently operating the following pilot-scale fluidized-bed reactors:

- Fluidized-bed mild gasification reactor
- Fluidized-bed catalytic reactor for the production of hydrogen
- Pressurized fluidized-bed combustor

The Center is also planning to install and operate a transport reactor test unit (TRTU) to provide scaleup data for the hot-gas cleanup test facility in Wilsonville, Alabama. Table 1 shows the typical operating parameters of the various reactor systems.

3.0 RESULTS AND CONCLUSIONS

3.1 Particulate Control

In order to investigate particulate control methods, a test loop (Figure 1) was constructed and inserted into the exhaust piping of the advanced concept reactors at the Center. The test loop provides a means of exposing various hot-gas cleanup systems to actual product gases from coal gasification and combustion using fluidized-bed reactors. Long-term effects on hot-gas cleanup systems can be studied economically by passively participating in the various research gasification and combustion runs. Filter efficiency, strength degradation, changes in permeability, and corrosion resistance are being investigated, as well as other pertinent issues such as cleaning techniques and temperature/pressure effects.

The test loop was constructed using high-alloy metals with no refractory in order to minimize maintenance and to avoid ash/alkali/refractory interactions that may occur due to the high surface-to-volume ratio present in smaller-scale systems. The alloys used in construction were Haynes alloys HR-160 and 556 and 316H stainless steel. The piping used in the highest-temperature regions was HR-160 and 556. It is expected that these alloys will demonstrate good high-temperature corrosion characteristics under both oxidizing and reducing conditions. The test loop is designed to operate at temperatures up to 1650°F and pressures up to 150 psig. The system was designed in accordance with B31.3 piping codes. The test loop consists of a single inlet pipe that branches into three different flow paths. Each path is controlled by a high-temperature valve located as far downstream as possible in order to minimize thermal stresses in the valves. Two of the flow paths are identical and are used as filter element test bays, and the third branch is used as a bypass line. Filter elements can be installed in either or both test bays simultaneously. The filter modules are flange-mounted so that they may be replaced as necessary for different filter types. The maximum filter housing dimensions are approximately 72 inches in length and 36 inches in diameter. Figure 2 shows the filter housing currently in use. The flanges used will permit operating conditions up to 1500°F and 150 psig. In order to achieve operating conditions up to 1650°F and 150 psig, further engineering is required to ensure that the flanged connection satisfies the criteria of the B31.3 piping code. The system will not be operated above 1500°F and 150 psig until this work has been completed. Gas flow rates through the various paths can be regulated by the downstream valves. The piping system is heated electrically using guard heaters. Pipe temperatures can be maintained at 1650°F continuously so that the process gas temperature can be raised or maintained as required in order to simulate the desired hot-gas conditions. The system has a heated backpulse system capable of delivering pressurized, heated, inert gas to the filter modules for cleaning purposes. The inlet piping to the test loop can be connected to a 100-lb/hr fluidized-bed gasifier or to other reactors being used for research at the Center. The TRTU is expected to be operational sometime in early 1993 and will be installed near the 100-lb/hr fluidized-bed reactor. The test loop will be connected to the TRTU when it is ready for operation.

TABLE 1

Operating Parameters and Specifications for the Hot-Gas Cleanup Test Loop

Operating Mode	Mild Gasification	Hydrogen Production	PFBC	TRTU	
Gas Flow Rate (scfh)	2,000	1,300	30,000	20,000	
Gas Temperature (°F)	1,100-1,650	1,200-1,500	1,000-1,650	1,400-1,650	
Gas Pressure (atm)	1-10	1	1-10	1-10	
Dust Loading (ppm)	TBD	TBD	TBD	TBD	
				Gasification	Combustion
Gas Composition (nominal)	85% N_2, 10% CO_2, 5% H_2O (see Note 1) 120 ppm H_2S	57% H_2O, 18% H_2, 14% CO_2, 6% CO, 5% N_2, 1%-2% CH_4	69% N_2, 15% CO_2, 12% H_2O, 4% O_2	53% N_2, 16.5% CO, 11.5% H_2, 9.5% H_2O, 8.5% CO_2, .5% CH_4	75.5% N_2, 15.5% CO_2, 7% H_2O, 2% O_2
Backpulse Cleaning					
Gas Composition	Nitrogen				
Gas Temperature (°F)	1500				
Gas Pressure (psia)	300				
Pulse Duration (sec)	Variable				
Tube-Sheet Cooling	Steam				
Steam Pressure (psia)	110				
Steam Flow Rate (lb/h)	500				
Steam Inlet Temp. (°F)	330				
Sampling Apparatus	TBD				
Analytical Apparatus	TBD				

Note 1: There is no single set of operating parameters for the mild gas calciner since it could vary considerably depending on the heating/fluidizing gas. Ranges to consider should be N_2 = 65% to 85%; CO_2 = 10% to 30%; H_2O = 0% to 10%; CO = 1% to 5%; H_2 = 1% to 5%; CH_4 = 1% to 2%; and H_2S = 100 to 2000 ppm.

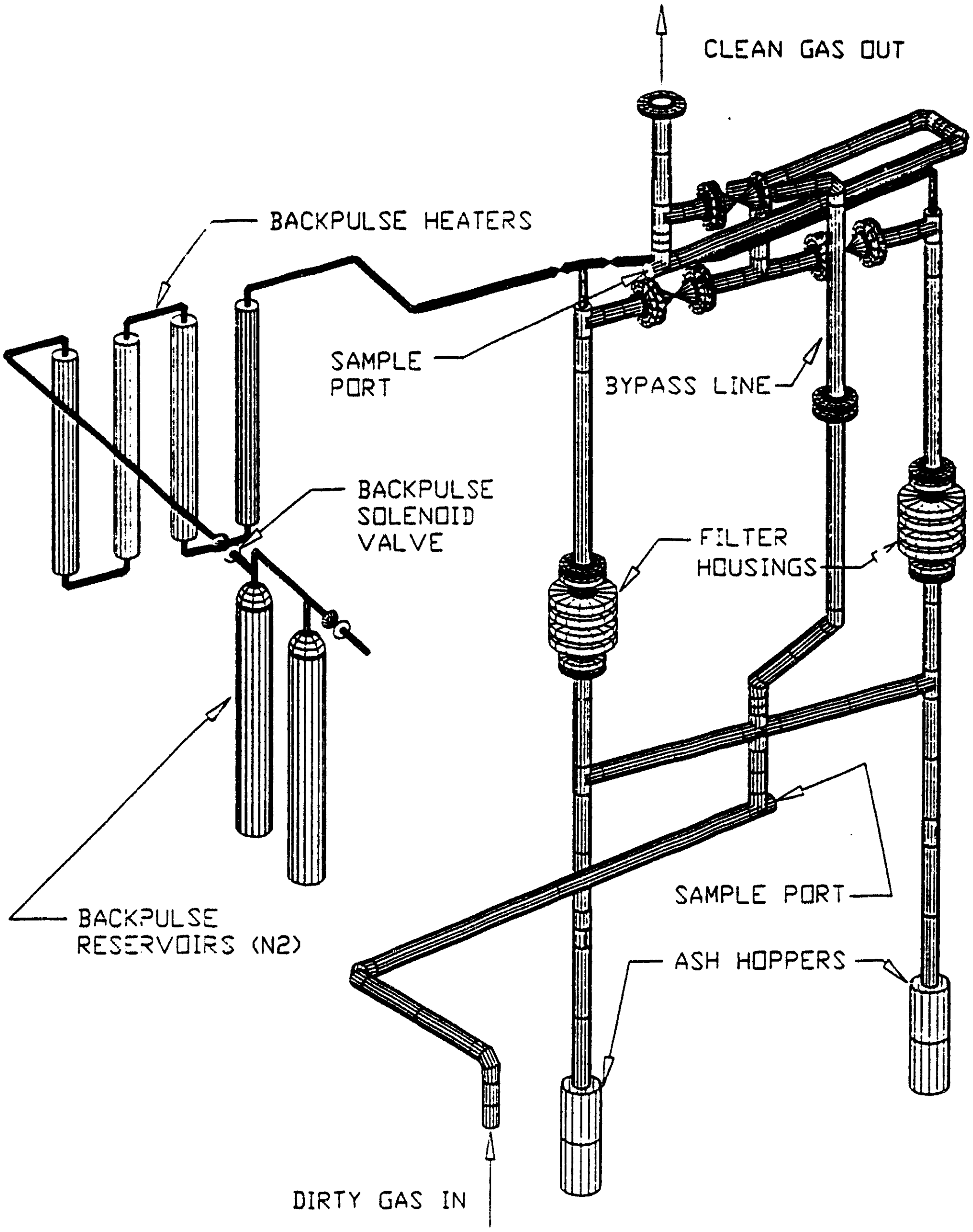


Figure 1. Hot-gas cleanup test loop.

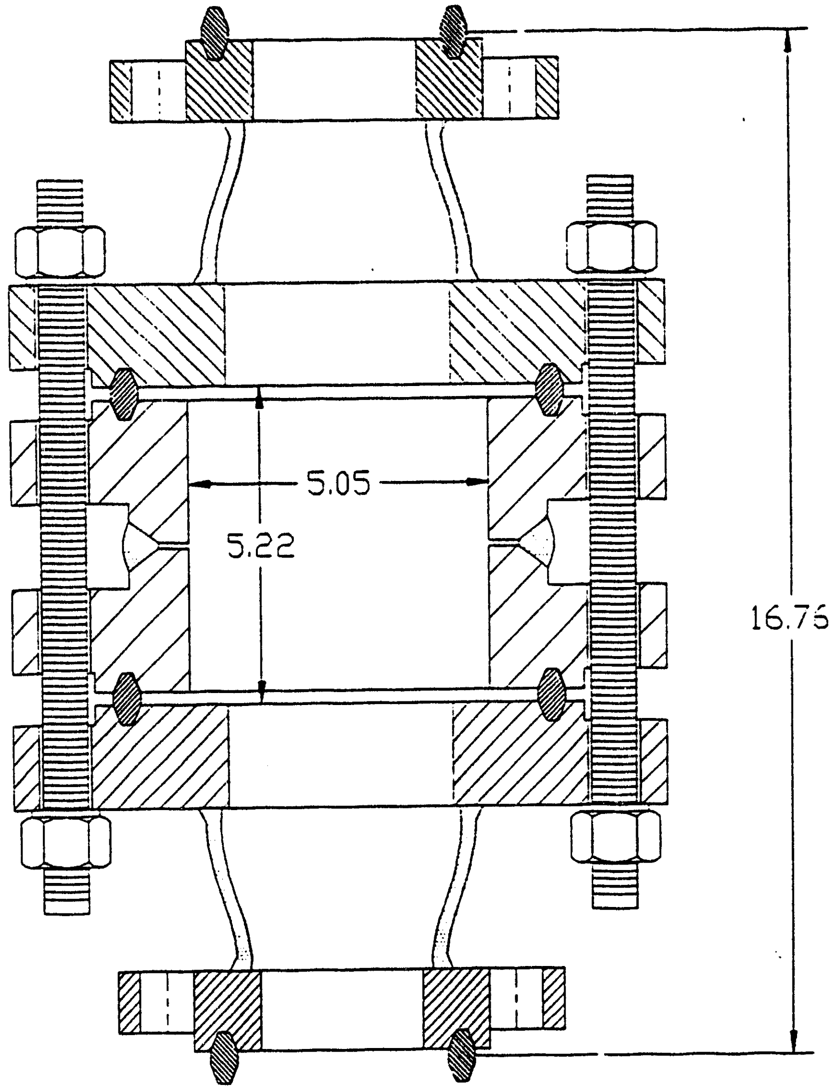


Figure 2. Filter housing currently in use.

The performance of the backpulse cleaning system was characterized to determine the available cleaning capabilities of the system. The actual cleaning requirements will be dependent upon the hot-gas cleanup system being evaluated. Modifications to the pulse cleaning system may be necessary as dictated by these requirements.

A high-temperature, high-pressure, particle sampling system is being developed for use with the hot-gas cleanup test loop. This sampling system must meet the National Electrical Code (NEC) and B31.3 piping requirements, as well as allowing sampling at the extreme operating conditions of the test loop. Aside from code-related issues, the particle sampling system currently in use is slow and cumbersome to use. A separate probe must be inserted to make flow measurements, then the particulate probe must be inserted to make dust-loading measurements. It takes approximately 45 to 60 minutes to collect one sample with the current configuration. While this system may be adequate for intermittent measurements on a temporary basis, it is inadequate for safe, reliable, long-term work. The particulate sampling system is being designed to sample at pressures up to 200 psi at a temperature of 1800°F under both oxidizing and reducing conditions. Table 2 shows the performance specifications for the sample system, and Figure 3 shows the sampling system. A sampling probe is inserted into the test loop, and a particulate sample is withdrawn isokinetically. The sample probe is considered to be disposable (based on wear). Different materials will be used for different operating conditions. The gas sample will pass through a series of cyclones and a borosilicate filter to remove all particulate matter, then through a quench train to remove any condensables, then through gas meters to determine flow. The probe and cyclone assembly will be electrically heated to maintain the gas temperature until it reaches the quench train.

The test loop is scheduled to be operational by the time the transport reactor is ready for shakedown testing. Recommendations for future work include testing and calibrating the particulate sampling system and evaluating various filter candidates in the test loop in conjunction with other research activities.

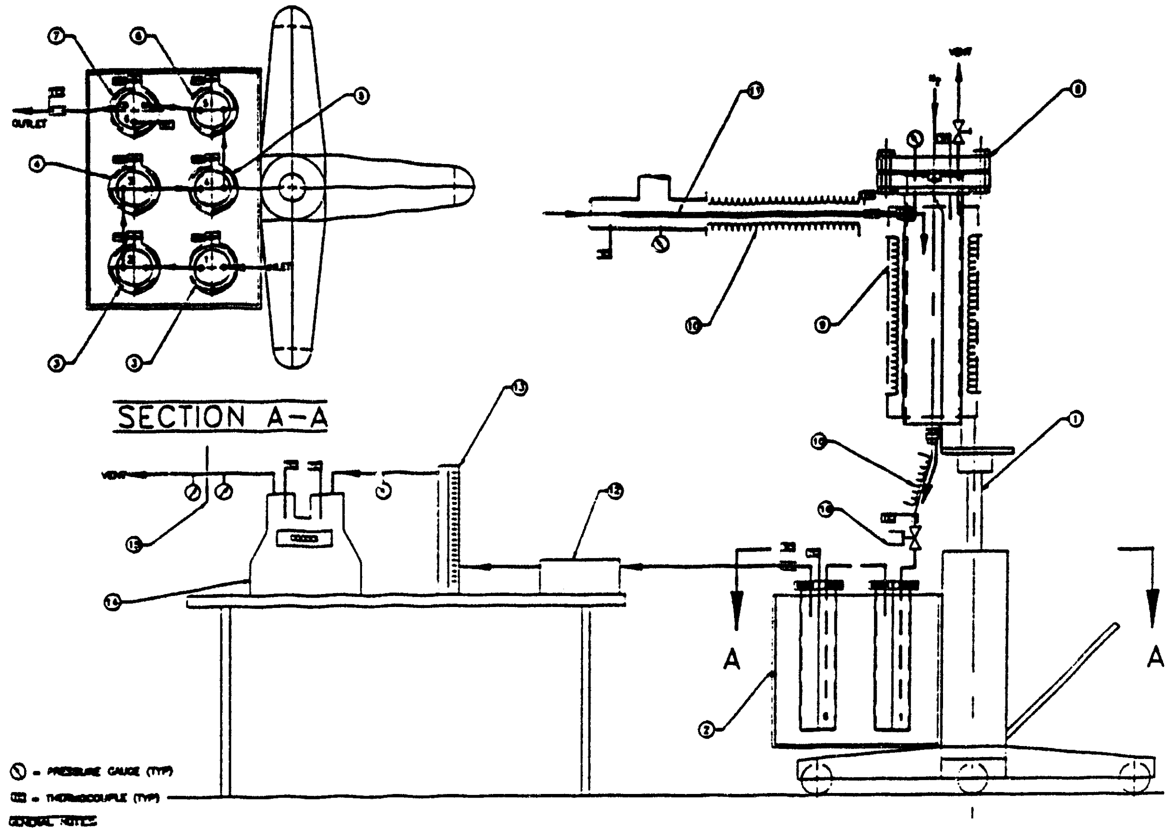
3.2 Alkali Getter Testing

Tests of kaolin as an entrained alkali getter in atmospheric and pressurized coal combustion systems were performed with the EERC pressurized drop-tube furnace (PDTF) system. Kaolin is a clay composed primarily of the mineral kaolinite ($Al_2Si_2O_5[OH]_4$). In pressurized fluid-bed combustion tests using granular filter beds, clays have been shown to be good sorbents for removing alkali compounds from the gas stream (1). In laboratory studies, kaolin has been shown to be effective not only at removing sodium compounds from the gas phase, but also in irreversibly fixing the sodium (2). Other clays are also believed to absorb sodium compounds from the furnace gas when the clay is added to the coal feed. Emathlite has been shown to be especially good at gettering sodium (2).

TABLE 2

Specifications for an Isokinetic Particulate Sampling System

Maximum Inlet Gas Temperature	1,800°F
Maximum Inlet Gas Pressure	200 psig
Gas Flow Range	2,000 - 30,000 scfh
Maximum Gas Temp. @ Filter	1,000°F
Typical Sample Rate	One Sample per Hour
Gases to be Sampled	Exhaust Gases from Coal Combustion and Gasification (reducing and oxidizing)
Electrical Classification (NFPA)	Class I, Div. 2, Group B
Applicable Codes	ASME B31.3 Piping Code



QTY	ITEM	PART NO	DESCRIPTION	MATERIAL SPEC
	17			
1	16		FLOW CONTROL VALVE	
1	15		ORIFICE METER	
1	14		DRY GAS METER	
1	13		FLOW METER	
1	12		OIL TRAP WITH INDICATOR	
1	11		SAMPLING PROBE ASSEMBLY	
2	10		HEAT TRACE LINE	
1	9		HEATER, SPLIT SHELL, CERAMIC	
1	8		PARTICULATE SAMPLING ASSEMBLY	
1	7		ADSORBER, MOLECULAR SIEVE	
1	6		ADSORBER, ACTIVATED CARBON	
1	5		BUBBLER, SILICA GELL	
1	4		BUBBLER, DRY	
2	3		BUBBLER, SOLUTION	
1	2		GAS CONDITIONING TRAIN	
1	1		POSITIONING JACK, 2 STAGE PORTABLE	

ENERGY AND ENVIRONMENTAL RESEARCH CENTER
GRAND FORKS, NORTH DAKOTA, U.S.A.

PARTICULATE SAMPLER ASSEMBLY

TOLERANCES UNLESS OTHERWISE SPECIFIED FRACTIONAL ± 1/16 3 PLC DEC ± 0.005 2 PLC DEC ± 0.030 1 PLC DEC ± 0.1 ANGULAR ± 2-1/2 DEGREES	DRAWN BY: DMB	DATE: 1-10-92	FUND NO: 4358
	CHECKED BY: WRK	DATE: 1-14-92	WORK REQ: WI
	PROJ. MGR: GLS	DATE: 1-14-92	REV: SCALE: 1:4
	APPROVED BY:	DATE:	SHEET 1 OF 1
	FINAL ASSY:	NEXT ASSY:	DWG. NO: 1076

Figure 3. Test loop particulate sampling system.

To be an effective getter, the clay material must not deposit once the sodium is fixed. This implies that the gettering material must be composed of small particles, typically less than 5 μm in diameter, which will not separate from the flow of gas until collected in the particulate control system. Since clay particles normally have diameters smaller than this, they would appear to be ideal gettering agents. However, moist clays can be highly agglomerated due to surface moisture, so it is best if the clay feed is dry before feeding to reduce agglomeration.

Kaolin was preferred for the gettering test over other types of clays because it can be found in relatively pure form, containing less alkali and alkaline earth elements, which may flux the material upon heating. Also, kaolinite has a layered structure composed of a sheet of silica tetrahedra bonded on one side to a sheet of aluminum hydroxide octahedra, so it has a higher aluminum-to-silicon ratio than most other clays. Because of its higher aluminum content, and alkali fluxed particle will usually have a higher melting point than if it contained more silica. Kaolin is mined in a number of places in the United States and can be supplied in rock, dried powder, sieved dried powder, or slurry forms.

Although a small body of data is available about the getters in laboratory experiments, only limited data are available about the use of kaolin under carefully controlled coal combustion conditions, and no data are available about its use in pressurized coal combustion conditions. Therefore, four tests were performed to test the efficacy of kaolin as a getter in both atmospheric and pressurized coal combustion conditions, and to determine the mechanism of gettering. The kaolin used for these tests was provided as rock by J.M Huber Corporation of Macon, Georgia. It was dried, then ground with a mortar and pestle. Only fine powder was used for the gettering experiments.

The kaolin powder was mixed with pulverized coal from the Spring Creek mine, Montana, in the ratio of 1 part kaolin to 2 parts ASTM coal ash. Spring Creek coal was chosen because it has relatively high sodium and low ash contents and because the sodium is present in the coal as an ion associated with carboxylic acid groups in the organic structure of the coal. Because of this association, the sodium is vaporized during combustion. Vaporized sodium that encounters an ash particle is typically absorbed by the particle. However, Spring Creek coal produces little ash, so much of the sodium remains in the vapor phase in the hot zone of the combustor. In cooler regions of the boiler, it may condense homogeneously to ultimately form submicron sodium sulfate particles. There is some contention as to whether sodium hydroxide condenses, then sulfates, or sodium sulfate directly condenses. Both vapor phase and condensed sodium phases are very reactive and could cause severe corrosion of ceramic hot-gas particulate pollution control devices such as candle or cross-flow filters. Therefore, Spring Creek was chosen as a "worst-case" example of a coal that may cause alkali corrosion of ceramic hot-gas cleanup devices.

Four combustion tests were performed in all: one test each of raw Spring Creek at atmospheric pressure, coal plus kaolin at atmospheric pressure, raw coal at 100 psi, and coal plus kaolin at 100 psi. The tests were performed in the EERC PDTF, which is described in detail in the July through December 1991 semiannual technical progress report for the Turbine Combustion Phenomena project being performed under the

Cooperative Agreement at the EERC. The PDTF is capable of operating under the following conditions:

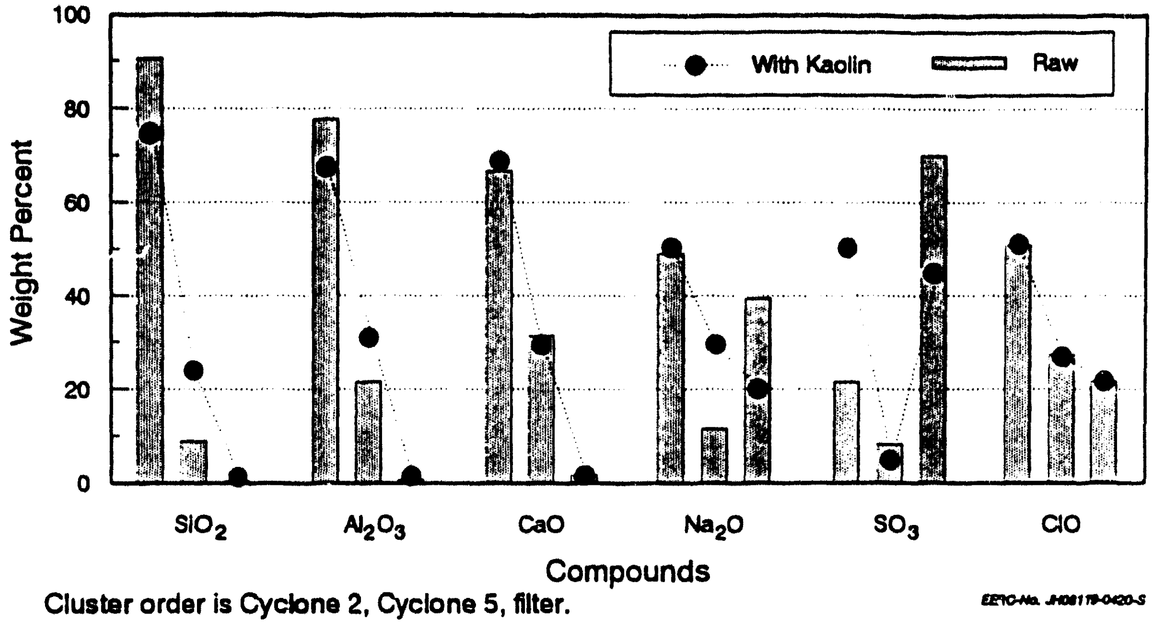
Temperature:	Ambient to 2732°F (1500°C)
Pressure:	Ambient to 300 psia (20.4 atm)
Oxygen:	0 to 20 mol%
Gas Flow:	0 to 7.8 scfm (220 L/min)
Residence Time:	0 to 5.0 sec

- Optical access at any residence time
- Provision for char and ash collection
- Provision for ash deposition studies

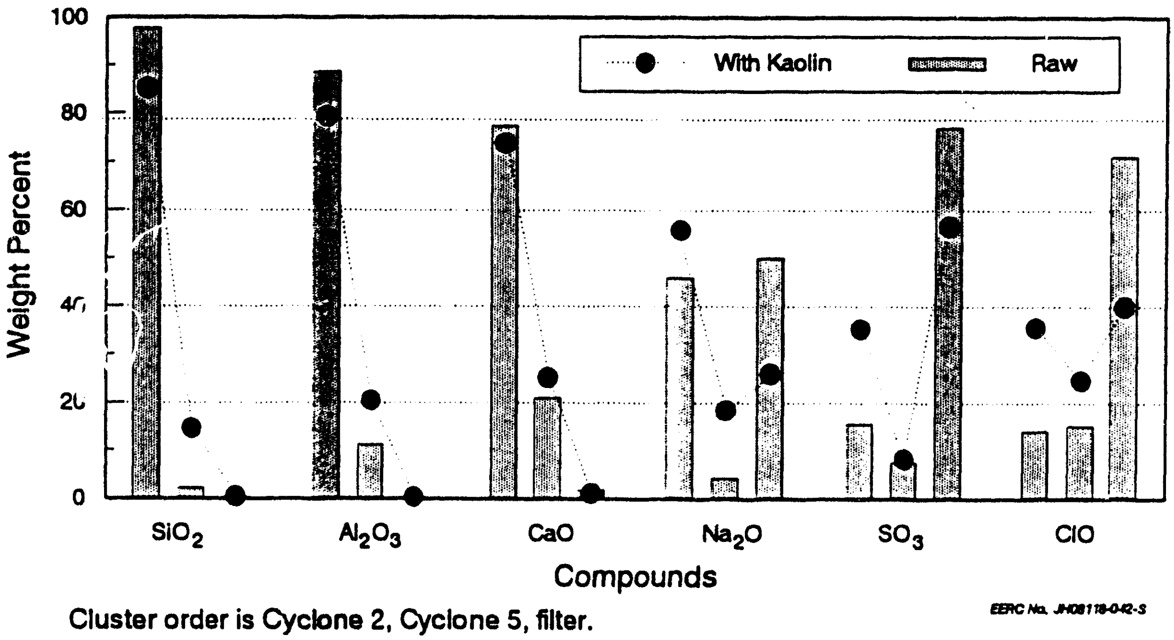
For the entrained kaolin tests, fly ash samples were collected and size-segregated on-line with a series of two cyclones and a final nylon filter. To determine the efficacy of the kaolin additions in gettering, the weight distribution of elements among the different size ranges was used. Figure 4 shows two combination bar-line graphs that illustrate the weight percent of the major elements that were collected for each test in each size range. Two graphs are used, one for the pressurized tests, the other for the atmospheric tests. The bars represent the values for the raw coal tests, the lines represent the values for the test of the coal/kaolin blend. For each element, the three data points, from left to right, are for the larger cyclone, the smaller cyclone, and the filter samples, respectively. Because different flow rates were used for the atmospheric tests versus the pressurized tests, the cut points of the cyclones were different, so the data should not be used to determine changes in weight distributions due to pressure, only changes due to the addition of the kaolin. Attempts to measure the actual size distributions of the collected samples via laser light scattering (Malvern) were not completely successful because of particle agglomeration. In general, however, particles collected in Cyclone 2 (larger cyclone) had diameters greater than 10 microns, in Cyclone 5 (smaller cyclone) the diameters were between 1 and 10 microns, and on the filter they were less than one micron in diameter.

Because the cyclones had different size cut points for the atmospheric versus pressurized tests, the effects of pressure on the size distributions of the elements are somewhat ambiguous. It is clear that the relative weight distributions of all elements except chlorine among the different particle sizes are not strongly affected by pressure. In each case, silicon, aluminum, and calcium all tend to be predominantly concentrated in the larger particles, with negligible fractions present in the submicron particles. In contrast, large percentages of the sodium, sulfur, and chlorine are found in the smallest particles. Sulfur was bimodally distributed, most likely present as calcium sulfate in the largest particles and as sodium sulfate in the smallest particles. In the raw coal tests, chlorine shows the only significant size shift due to pressure increase, from larger to smaller particles. The chlorine-containing particles in the smallest size range probably formed as the gas was quenched during sample collection, indicating that at higher pressure more chlorine (probably as chloride) may exist in the gas phase than at atmospheric pressure.

The most important conclusion about the gettering tests is that sodium is shifted strongly away from the smallest particles by the addition of kaolin. If we assume that the sodium sulfate in the smallest size fraction formed through homogeneous nucleation as the gas cooled (possibly during collection), then one half of the sodium was removed from



(a) Percent of each element in each size fraction in the atmospheric pressure tests.



(b) Percent of each element in each size fraction in the high-pressure tests.

Figure 4. The percent of each element collected in each size fraction for the tests of kaolin as an alkali getter.

the gas phase by the kaolin addition. This result holds both at atmospheric and higher pressure. Most of the sodium was shifted to the 1- to 10-micron size range, which is where the kaolin is concentrated. The concurrent shift in sulfur from the smallest to the largest size ranges indicates that the sodium was chemically combined with the kaolin, probably in the high-temperature zone, and that the kaolin did not merely serve as a condensation surface for sodium sulfate. Because much of the sodium was removed from the gas phase, the sulfur shifted to the largest size range by sulfating relatively more of the calcium-rich particles.

3.3 Thermochemical Equilibrium Modeling: PHOEBE Database Modifications

PHOEBE (PHase Ordering and EquiliBrium Evaluation) is a computer program developed at the EERC to calculate the thermochemical equilibrium composition of combustion products. The following objectives had been set forth for the improvements of the model for this year:

1a Improve PHOEBE database
2b Run simulations

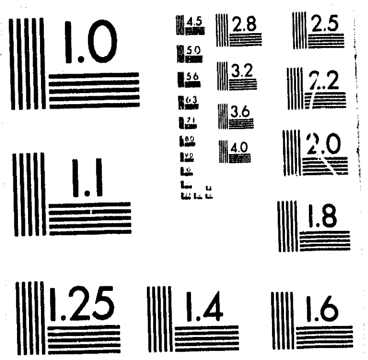
Both items were addressed and are now complete. Item 1a, the improvements to the PHOEBE database, required a substantially (approximately 4 months) longer period of time than had been originally anticipated. However, the database now contains about 850 species, which is a threefold increase from its former size of about 270 species. Additionally, the database has also been thoroughly cross-checked. Validation tests have also been conducted and the database modified depending on the results of these tests. We also wish to emphasize that we expect the updating and validation process to be an ongoing activity throughout the lifetime of this project.

A list of chemical compounds relevant to advanced coal combustion systems was compiled. A variety of vapor- and liquid-phase species was specifically chosen to better represent fluidized-bed combustion systems. The requisite free energy of formation (FEF) data for each species were also collated and entered into the database. The current PHOEBE database contains approximately 370 chemical compounds with an average of more than two physical phases (gas, liquid, or solid) per compound. This makes a total of roughly 800 species, which is a threefold increase over the original database.

The original PHOEBE database was modified to a free-form ASCII database (FAD). This has the advantage that any conventional text-editing software can be used to edit the database. Also, since almost any text editor or word processor may be used to update, modify, or edit the database, specialized software to perform these tasks becomes redundant.

A database management utility that performs searching, retrieval, indexing, etc., was written (in C), debugged, tested, and is fully operational. Although these tasks can also be accomplished by some of the more advanced word processors, their specialized nature prohibits their execution by generic text editors.

Routines to curve-fit the FEF data of the species have also been written. These routines allow a wide variety of representations (linear, polynomial, rational, logarithmic, etc.). The curve-fit representations of the FEF data can thus be chosen in the most


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3

optimal manner. In most cases, the curve-fitted FEF data are used, if need be, at the computation level.

The thermodynamic systems simulations of Item 2b have also been completed. Initially, very simple systems (like water, gas mixtures, etc.) with well-characterized thermodynamic behavior were simulated to validate the correctness of the overall PHOEBE algorithm, as well as to optimize the standard free energy of formation values for many of the species in the database. A total of about 20 such simple systems were simulated. During this stage, the algorithm also underwent a few iterations of revisions and changes. Two systems were selected for the final phase of this task item and their equilibrium behavior simulated. They were the Al_2O_3 - SiO_2 system and a portion of the Na_2O - Al_2O_3 - SiO_2 system. A comparison of the simulation results with the experimental phase diagrams shows acceptable results, the largest error in the simulated results being about 70°C in liquidus temperature for either system tested. Figure 5 is a plot of the experimental versus predicted phase diagram of a cross section of the ternary system Na_2O - Al_2O_3 - SiO_2. As can be seen from the figure, the predicted values track the experimental values well. It should be noted that both these systems were assumed to behave ideally (i.e., with unit-activity coefficients), so, necessarily, we expect errors in the predicted values since no system is ideal. Additionally, it must also be borne in mind that inherent inaccuracies exist in the FEF values in the database. All in all, therefore, it can be concluded that PHOEBE provides acceptably accurate representations of the equilibrium behavior of multiphase, multicomponent systems.

Na_2O–Al_2O_3–SiO_2

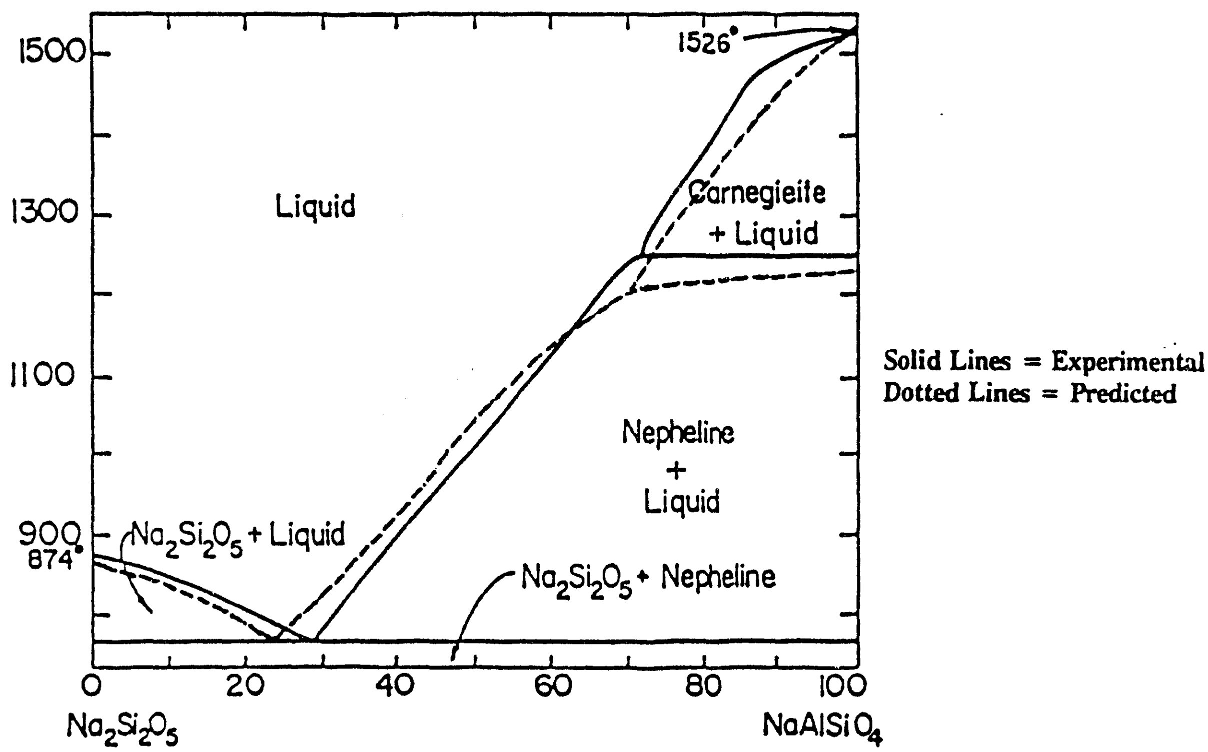


Figure 5. A plot of the experimental vs. predicted phase diagram for a cross section of the Na_2O - Al_2O_3 - SiO_2 system.

4.0 FUTURE WORK

Future work will involve the use of PHOEBE to determine the most efficient combinations and quantities of alkali getters to use in combustion tests. In addition, alkali attack of ceramic materials that could be used in the construction of ceramic particulate filters will be investigated both with the PDTF and in laboratory experiments.

Future opportunities for the EERC to utilize the hot-gas test loop are numerous. The EERC can be utilized in a supporting role for the Wilsonville hot-gas cleanup facility by functioning as a screening facility for emerging cleanup technologies that lack long-term operating histories. As additional operational issues arise at Wilsonville, they may be addressed economically at the EERC.

The test loop will also be utilized for testing of new filter materials that are identified as a result of the bench-scale work done investigating alkali attack issues.

The EERC is also planning on establishing a consortium of hot-gas cleanup device developers for the purpose of operating the test loop for extended periods to provide performance data on the candidate cleanup systems.

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3.0 ADVANCED RESEARCH AND TECHNOLOGY DEVELOPMENT

3.1 Turbine Combustion Phenomena

TURBINE COMBUSTION PHENOMENA

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

by

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December 1992

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

TABLE OF CONTENTS

LIST OF FIGURES

TURBINE COMBUSTION PHENOMENA

1.0 INTRODUCTION

The main obstacle to widespread use of low-rank coals (LRCs) for applications other than minemouth power generation is their high moisture, sometimes over 60%. Conventional evaporative drying can remove all the moisture and produce a dried fuel that is acceptable if used immediately. However, no known evaporative process, including those followed with expensive oil coating, yields a dried bulk LRC that can withstand the rigors of shipping and handling. Evaporatively dried LRCs act like sponges and reabsorb moisture when exposed to high humidity. They generate copious amounts of dust when handled and are prone to spontaneous combustion (1,2,3).

Coal-water mixtures (CWMs) technology is commercially available for high-valued bituminous coals using costly additives. Adding to the cost of bituminous CWMs is the requirement to include expensive micronizing to offset the inherent low reactivity, particularly for advanced applications. Recent advances in hydrothermal treatment of cheaper, more reactive LRCs at the University of North Dakota Energy and Environmental Research Center (EERC) have enabled LRCs to be used in CWMs. Hydrothermal treatment, commonly called hot-water drying (HWD), (4,5) is a high-temperature, nonevaporative drying technique carried out at high pressure in water, during which the structure of the LRC is permanently altered. The process can be viewed as permanent moisture reduction through induced coalification with reuse of the water removed to slurry the HWD coal. HWD produces a coal-water fuel (CWF) with about the same energy density as the feed coal, while retaining the high reactivity of the LRC. HWD low-rank coal-water fuels (LRCWFs) usually do not require costly additives, while yielding pseudoplastic fluids even at the extreme shear rates seen during atomization. Estimates of process economics have indicated that a minemouth HWD plant in the Powder River Basin can produce a LRCWF at around $1.50/MM Btu, including coal costs.

Combustion tests assessing the technical feasibility of burning hydrothermally treated LRCWF in a atmospheric, bubbling fluidized-bed combustor (FBC) were performed at the EERC (6). A low-rank CWF prepared from a Powder River Region subbituminous coal was successfully burned in a 18- x 18-in FBC. The 60 wt% dry solids CWF was pumped directly into the dense-bed zone of the combustor through a simple, water-cooled pipe without the aid of a nozzle or atomizing air. Operation of the combustor was extremely stable when firing with the CWF and a coal-water/limestone fuel mixture. Carbon burnout was very high, ranging from 99.4 to 99.7%, which is equal or slightly greater than those obtained from screw feeding the same coal. NO_x emissions were significantly lower than those seen burning the "as-received" coal. Limestone utilization was the same for the limestone added to the CWF as it was for the separate dry limestone feed.

The combustion behavior of hydrothermally treated LRCWF have been investigated in a 550,000 Btu/hr ash fouling furnace at the EERC (7) and a 400,000 Btu/hr vertical laboratory-scale combustor at Brigham Young University (8). Essentially complete carbon burnout (99+%) was achieved in most tests with residence times as short as 1.4 seconds. The LRC fuel combustion was more stable than high-rank CWFs combusted in both combustors under comparable conditions. Both projects reported that the LRC fuels were not as dependent on the quality of the atomization as were the high-rank fuels. The higher stability of the LRC fuels have been attributed to a higher percentage of volatile matter, higher reactivity, and nonagglomerating properties. Lower volumetric heat release rates have been measured with LRC fuels, as compared to the high-rank bituminous CWF, indicating the need for larger boilers with LRC fuels, which is consistent with current boiler practice using pulverized fuels. Compared with pulverized fuels, the flame produced in CWF combustion is distributed further through the furnace combustion zone with lower peak temperatures. Analyses of deposits produced in combustion of pulverized LRC fuels were primarily simple oxides and sulfates, while the deposits from the combustion of CWF were predominantly complex aluminosilicates.

Traditionally, heat engine fuels have been limited to clean fuels, such as natural gas or distillate fuels, which minimize the interrelated degradation processes of deposition, erosion, and corrosion. A coal-water slurry fuel has the potential of being injected and burned directly in a gas turbine or diesel engine utilizing injection and fuel handling methods similar to those employed with heavy petroleum fuels. Burning coal in a gas turbine is not a new idea, but commercial success has not been achieved. Under DOE sponsorship coal-water slurry fuels have been investigated as fuels for gas turbine engines for several years, but the major technical problems inhibiting commercialization are 1) deposits on the pressure and suction sides of the turbine blades reducing the gas flow area and turbine efficiency, 2) acceptable coal burnout given the short residence times inherent with gas turbine combustors, 3) corrosion of turbine blades by condensed alkali sulfates, 4) erosion of turbine blades and other components by ash particles entrained in the products of combustion, and 5) emissions control of NO_x, SO_2, and particulates. The release of certain mineral matter species found in both raw and beneficiated coals can lead to ash deposition on surfaces, regardless of the ash content of the fuel. This deposition can lead to corrosion and metal loss of critical turbine components and, ultimately, to derating, unavailability, or catastrophic failure of the power generation system. Alkali metals and sulfur, existing as impurities in coal, have been identified as key components in the initiation of deposition and the onset of corrosion.

The efficient operation of advanced heat engine combustion systems depends on high CWF carbon burnout under short residence times. Atomization quality of CWF is an important parameter related to high carbon burnout in these systems. It has been reported that atomizing air-to-fuel mass flow ratio, relative velocity between the air and fuel, fuel velocity, and slurry rheology affect atomization performance. In addition, research efforts have indicated that additional factors such as extensional viscosity and coal particle agglomeration also might be important (9).

Combustion tests to evaluate the combustibility of LRCWF in a pressurized staged combustor were completed at the United Technologies Research Center (10). Conclusions from this research were that high levels of combustion efficiency can be achieved when firing LRCWFs, provided an adequate fuel energy density is available. A minimally processed Eagle Butte subbituminous CWF, which was limited to low coal loading (42 wt%) and low energy density to preserve acceptable handling, was incapable of sufficient heat release to sustain stable combustion. HWD Eagle Butte slurries possessed higher solids loadings (up to 55 wt%) and achieved stable combustor operation with high-combustion efficiencies (>95%). For the combustor used, a minimum heating value of 5000 Btu/lb was required to maintain stable and efficient combustion. Combustion efficiency was found to increase with increasing energy density of the fuel. A HWD Velva (North Dakota) lignite also provided stable and efficient combustor operation.

General Motors Allison Gas Turbine Division (GM Allison) has completed two combustion tests with LRCWFs made at the EERC with a Powder River Basin coal in their full-scale 70-MM Btu/hr rich-quench-lean gas turbine combustor (11). Ash analyses from these tests indicate that the carbon burnout was very high, exceeding 99.9% in most cases. This burnout was much higher than the nominal 98%+, which has been seen with a bituminous CWF. The collected ash was free of hard slag agglomerates or fused material. In addition, a four hour proof-of-concept combustion test was conducted on a Allison 501K gas turbine with excellent combustion performance. A water-washable deposit was formed on the leading edge of the turbine blades (12). The deposit was characterized as primarily sodium and sodium-calcium sulfates. Atomization of a hydrothermally treated subbituminous CWF was conducted at GM Allison, and results from these tests indicate that the subbituminous CWF atomized as well as or better than thirteen other CWFs made from bituminous coal atomized in their atomization test facility (13).

General Electric Transportation Systems has also burned hydrothermally treated LRCWF using a 7FDL two-cylinder diesel engine (14). The bore and stroke of this particular engine is 9" x 10.5" and is rated for 1050 rpm. The burnout rates of the subbituminous fuels used were very high (>99%), which was slightly higher than the bituminous CWFs, despite having a mean particle size three times higher than the particle size for the bituminous coal. No results have been presented on any increased injector wear caused by the LRCs higher ash levels.

2.0 OBJECTIVES

The overall objective of the Turbine Combustion Phenomena Program has been to expand the scientific and engineering database for the combustion of LRC fuels in advanced pressurized combustion systems, such as those found in gas turbine engine applications. Fundamental research on the use of low-rank coal slurries for gas turbine engine applications has developed data that will 1) quantify the potential advantages of LRC higher reactivity and nonagglomerating tendencies, 2) help in determining fuel specifications, and 3) indicate needed design modifications in the gas turbine engines themselves. The intent of this research has been to establish the relationships between LRC properties and gas turbine engine operational parameters and compare these relationships with those established for diesel fuel and bituminous coal slurries.

The investigation of turbine combustion phenomena at EERC was a multiyear program. Six-year goals were established and are discussed in the following text.

SIX-YEAR OBJECTIVES

1. Technology and Market Assessment. To ensure that all sources of information to the project are thoroughly researched, EERC has performed an extensive survey of all published information concerning the use of coal and coal slurries in gas turbine applications. This information provided an understanding of the concerns and needs for the use of coal-derived fuels in these applications. The

state-of-the-art for these technologies was determined and utilized to provide the proper direction for this program and limit duplication of effort. This effort has built upon a similar assessment of the market and technologies that was performed as a part of the Low-Rank Coal Slurry Combustion program.

2. Reactivity of Fuel in Pressurized Systems. The reactivities of dry and slurried LRCs are higher than those of bituminous coals, but the magnitude of these differerces was not well documented. Fast, simple, inexpensive experiments in a modified combustion bomb provided very basic information about the pressurized combustion behavior of LRC and slurries. This information is useful in determining the fuel specifications of slurries for use in heat engine applications. Data collected during these tests included the heat of combustion (calorimetry) of the sample, the sample burning time/reactivity (from pressure sensors), and the analysis of the products of combustion after combusting the test fuel under various conditions. Parameters to be studied included coal type, gas composition (percent oxygen), combustion bomb conditions at fuel injection, and system pressure. This testing provided semi-quantitative information in a fast and inexpensive manner.

3. Investigate the Fundamental Characteristics of Burning Low-Rank Coal Slurries in a Turbine System. A bench-scale gas turbine simulator was designed to measure the pressure, temperature, conversion, gas composition, vaporization of inorganics, deposition on simulated turbine blades and other system components, fuel reactivity, and ash particulate-size distributions resulting from the combustion of LRC slurries. These fundamental studies demonstrated the impact of various fuel properties on the combustor and turbine blades and led to the development of fuel specifications for the successful operation of low-rank slurries in a turbine application. This task continued throughout the first three years of the program.

4. Characterization of LRCs Atomization Properties. This task examined the pressurized atomization characteristics of LRC fuels with a Malvern 2600 particle-size analyzer and still photography in a pressurized spray chamber constructed at EERC. The combustion behavior of the previous fuels tested in the spray chamber and new fuels produced for the turbine project were evaluated under similar air-to-fuel and pressure ratios in the gas turbine simulator. This task also looked at different atomizer types in a effort to minimize spray-droplet-size distributions and increase combustion performance for a given rheology and atomizing air-to-fuel ratio.

5. Evaluation of LRC Fuel Agglomeration. The objective of this task was to evaluate the agglomerating or nonagglomerating tendencies of LRC fuels by sampling fly ash generated from slurry droplets at various positions along the axis of a pressurized drop-tube furnace recently constructed at EERC. Thus products of combustion particle-size distributions, as a function of residence time, and the starting particle-size distribution and droplet size can be measured to determine if the smaller particle-size distributions found in the LRC fly ash are the result of a gradual burnout of slurry droplet agglomerates or the result of agglomerate disintegration into its original particle-size distribution due to the high thermal friability of LRC fuels.

6. Hot-Gas Cleanup. This effort has assessed available technology to determine specific needs with respect to the removal of undesirable constituents from gas streams derived from high temperature/pressure combustion of LRC slurries, with emphasis on coal-specific problem areas. Initial work has been devoted to a review of the literature on the removal of contaminants from the coal-derived gas streams. Processes which are capable of removing >90% of sulfur and/or nitrogen oxides, >99% of particulates, and which reduce alkali vapors in the gas stream to < 25 ppm are desired. The reported work has been evaluated to establish applicability to LRC slurry utilization. A summary of reviewed papers and reports has been prepared to identify processes according to overall performance, thermodynamics, economics, and environmental considerations. Special consideration has been given to gas cleaning methods which produce a salable product or zero discharge of waste and are cost-effective. Work toward this objective will continue during the course of the program. This task was primarily focused on the investigation of particulate hot-gas cleanup systems. The objective of this task was to evaluate potential hot-gas particulate cleanup techniques as to their relative probability of success and test the best two or three systems in the turbine simulator. This task would include a technology assessment that would build upon a previous literature search performed on hot-gas cleanup techniques. These techniques could include, but would not be limited to, ceramic cross-flow filters and filter candles, nested fiber filters, cyclones, high-temperature/high-pressure electrostatic precipitators. This work involves tests with various CWFs in an effort to reduce fly ash particle-size distribution entering the deposition section of the turbine simulator to a minimum of 95% less than 5 microns in order to limit the amount of particle impaction on the turbine blades.

7. Ash Transformation Studies. The objective of this task was to investigate the ash transformations experienced by mineral matter in beneficiated LRC fuels. Very little research to date has investigated the effects of pressure and coal beneficiation on the reaction pathways taken by the mineral matter present in LRC fuels. These transformations should be dependent on the cleaning techniques used and the level of cleaning achievable on the various coal types. Mineral matter transformations of beneficiated LRC fuels under turbine operating conditions were investigated in a pressurized drop-tube furnace constructed at EERC. This drop-tube furnace is capable of combusting powdered coal particles under closely controlled conditions. The effects of residence time, temperature, pressure, atmosphere, and gas/fuel flow rates can be varied to examine their effects on ash transformations and carbon burnout. The drop tube also provides carbon burnout as a true function of residence time given the laminar gas flow. The effects of deposition probe temperature and the approaching gas velocity on the measured deposition rates can also be investigated. Another advantage of the pressurized drop-tube furnace is the small quantities of fuel (up to 1.0 gm/min) needed to conduct extensive deposition and burnout testing as compared to the turbine simulator (approximately 150 lbs/hr).

   In addition, high ash fusion temperature fuels are needed under the assumption that low melting temperature ashes will stick to the cyclone wall or the ceramic material and will not be easily removed or cleaned from the hot-gas cleanup device. Technical work in this task consisted of combustion tests using fuels doped with additives selected for their ability to increase ash fusion temperatures. These tests will measure the effect these additives have on the sticking coefficient and deposition rates measured at conditions similar to those utilized in previous deposition tests.

8. Investigation of Slagging Combustor Design. Should concurrent beneficiation of LRC studies at EERC indicate that acceptable ash levels and chemistry not be achievable, a vertically fired combustion zone would be built to replace the horizontally fired, rich combustion zone on the current turbine simulator. This modification would enable the combustor to operate in a slagging combustor mode versus the current nonslagging combustor mode. Work on this task would be dependent on the results of the work in progress and would be subject to DOE approval.

To meet the objectives of the program, a pressured combustion vessel was built to allow the operating parameters of a direct-fired gas turbine combustor to be simulated. One goal in building this equipment was to design the gas turbine simulator as small as possible to reduce the quantity of test fuel needed, while not undersizing the combustor such that wall effects would have a significant impact on the measured combustion performance. Based on computer modeling, a rich-lean, two-stage, nonslagging combustor was constructed to simulate a direct-fired gas turbine. This design was selected to maximize the information that could be obtained on the impact of LRCs unique properties on the gas turbine combustor and its turbomachinery. This combustor is a horizontally fired, refractory-lined, water-jacketed, two-stage combustion pressure vessel. This vessel is comprised of several removal sections for investigating combustor configuration and residence time effects. The combustor has a nominal 1-MM Btu/hr firing rate and is designed to operate at pressures up to 250 psig (18 atm) and lean zone exit temperatures of 2000°F (1100°C) with temperatures in the rich zone up to 2700°F (1480°C).

An objective which was added later to this project was to provide General Motors (GM) Allison Gas Turbine division with 20,000 gallons of CWF produced by the EERC's 6-ton per day (tpd) hydrothermal drying Process Development Unit (PDU). The slurry was procured in 5000-gallon lots and shipped to GM Allison Gas Turbine division in Indianapolis, Indiana, to be used in Allison's 70-MM Btu/hr pressurized gas turbine project. The test slurry characteristics were based on the recommendations of Allison and EERC personnel to ensure product quality. The main slurry characteristics specified were ash content, coal particle mean size, heating value, slurry viscosity, and sulfur concentration.

3.0 RESULTS

During the program, several production runs of LRC CWF were produced in conjunction with the Department of Energy (DOE) LRC beneficiation program at the EERC. Beulah lignite from North Dakota and Kemmerer and Spring Creek subbituminous coals from Wyoming and Montana were selected for pilot-scale processing because of their ability to be physically and chemically cleaned to approximately 2 wt% ash on the bench-scale. This treatment scheme includes physical coal cleaning by dense-media separation, wet grinding, chemical cleaning by nitric acid leaching, hydrothermal treatment, and final wet micronizing.

The physical cleaning step uses a dense-media separation process which consists mainly of classifying coal, feeding it into an air-actuated cone separator system, followed by a washing and recycling section. The clean coal was then pulverized and fed into a continuous acid-leaching column. This chemical cleaning was conducted using a 30 wt% slurry mixed with a 4 wt% nitric acid solution. The sample was concentrated using a solid-bowl centrifuge, reslurried, and fed into the HWD PDU.

The HWD treatment forces inherent moisture out of the coal structure using carbon dioxide formed during the decarboxylation of the coal, thereby increasing the heating value of the product fuel. Tars are also exuded from the coal structure during treatment, sealing the micropore structure, reducing the surface area, and increasing the hydrophobicity of the coal. After hot-water drying, coal product slurry was then concentrated to 60 to 70 wt% in a centrifuge, reslurried, and micronized to a CWF. An anionic dispersant, D319-2 (ammonium lignosulfonate), was added to the final CWF.

A two-stage, rich-lean, nonslagging combustor has been built to simulate the operating conditions of a gas turbine engine. Results from combustion tests on a 1-MM Btu/hr gas turbine simulator indicate that the LRC fuels exhibit superior burnout compared to the bituminous fuels due to their higher reactivity (15). During the course of this program, seventeen successful combustion tests using CWF were completed. These tests included seven tests with a commercially available Otisca Industries-produced Taggart seam bituminous fuel and five tests each with a physically and chemically cleaned, hot-water-dried (PC/AC/HWD) Beulah-Zap lignite and a chemically cleaned, hot-water-dried (AC/HWD) Kemmerer subbituminous fuel. Analyses of the emission and fly ash samples highlighted the superior burnout experienced by the LRC fuels as compared to the bituminous fuel even under a longer residence time profile for the bituminous fuel. The LRC fuels experience better burnout than the bituminous fuels. The LRC fly ash showed a decrease in particle size as compared to the starting fuel while the bituminous fuel showed an increase in particle size as compared to the starting fuel. These particle-size analyses provide some evidence of LRCs nonagglomerating properties as compared to bituminous fuels.

Statistical analysis of the carbon burnout data generated in a series of parametric combustion tests produced simple models to predict the carbon burnout achievable under a given range of operating conditions. These models indicate that fuel type has a significant effect on the measured carbon burnout. Figures 1 through 3 show the measured carbon burnout versus combustion air temperature, atomizing air-to-fuel ratio and fuel firing rate, respectively. These figures demonstrate that the LRC fuels had a carbon burnout of 98.2+% which was not significantly affected by combustion air temperature, atomizing air-to-fuel ratio or fuel firing rate. However, the bituminous fuel had a maximum carbon burnout of approximately 97% and decreased 2.3% for each 100°F decrease in combustion air temperature below 840°F. A decrease in the atomizing air-to-fuel ratio from 1.25 to 0.75 would result in a 7.9% decrease in the carbon burnout. In addition, each 100,000 Btu/hr decrease below the 1-MM Btu/hr maximum firing rate resulted in a 1.7% decrease in the measured carbon burnout. This information indicates that the bituminous fuel can perform almost as well as the LRC fuels in a base-loaded gas turbine scenario, but lacks the capability for turndown necessary in a peak-loaded turbine

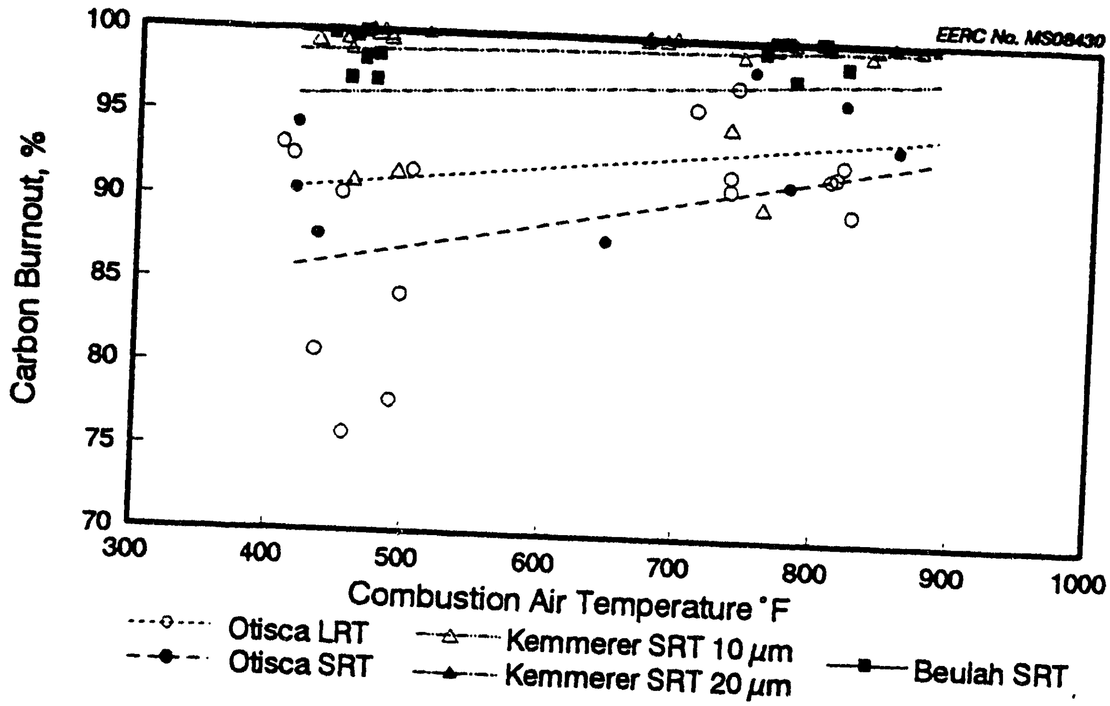

Figure 1. Graph of carbon burnout as a function of combustion air temperature for parametric combustion tests 43-47 (LRT = long residence time; SRT = short residence time).

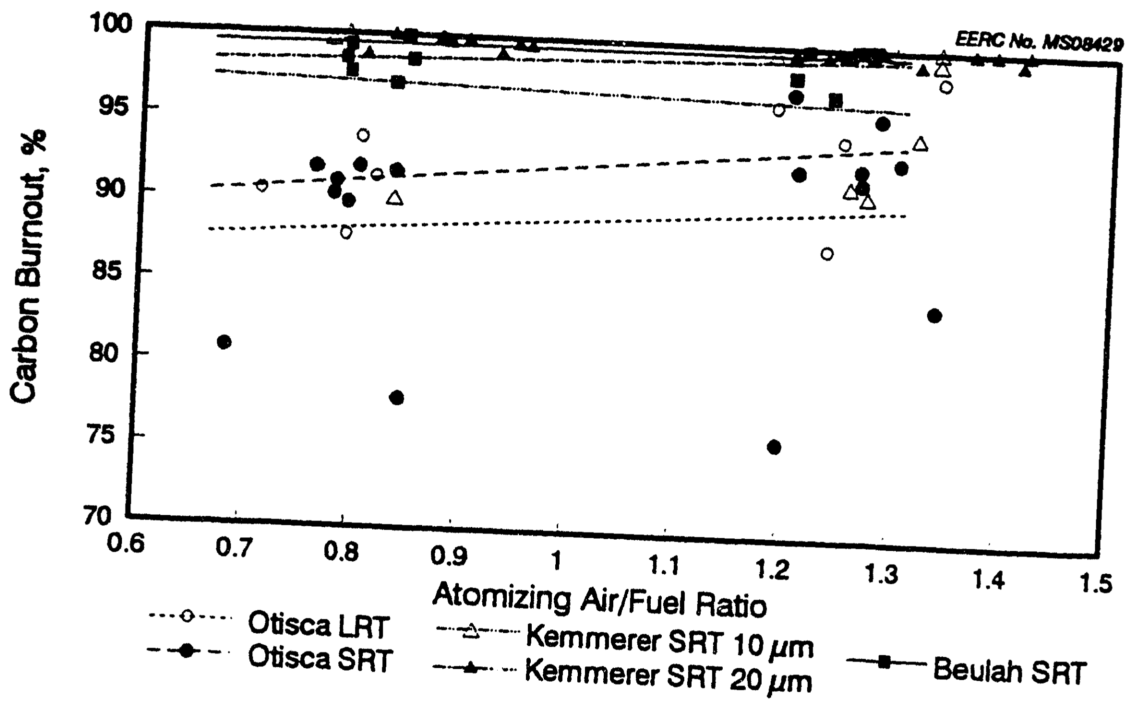

Figure 2. Plot of carbon burnout against atomizing air-to-fuel ratio for parametric combustion tests 43-47 (LRT = long residence time; SRT = short residence time).

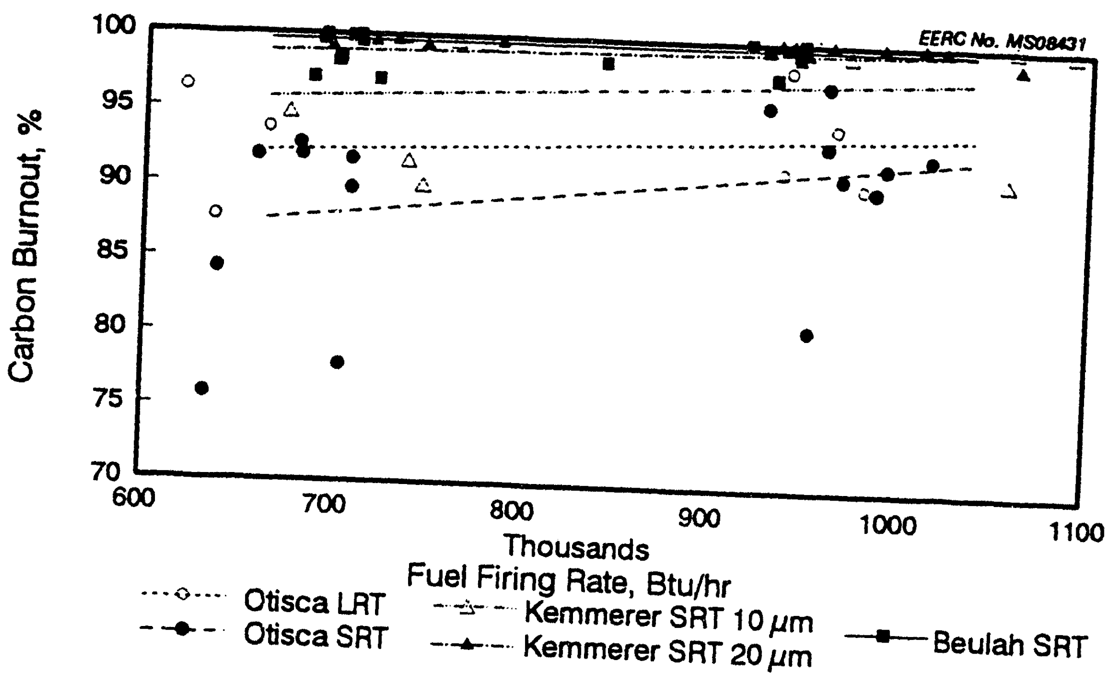

Figure 3. Plot of carbon burnout against fuel firing rate for parametric combustion tests 43-47 (LRT = long residence time; SRT = short residence time).

scenario. It should be remembered that this model is only valid between the ranges studied for the combustion air temperature (400° to 800°F) and fuel firing rate (0.7 to 1.0 MM Btu/hr).

As might be expected with the relatively high ash in the Beulah-Zap coal and lower ash fusion temperatures, significant ash deposition and slagging occurred in the turbine simulator. The x-ray diffraction analysis suggests that the residual magnetite left from the physical cleaning process remains as magnetite in the reducing atmosphere of the rich zone but is converted to hematite when it reaches the highly oxidizing atmosphere encountered in the lean combustion zone. As indicated by material balances, the low-rank slurries had significantly larger deposits than the Otisca slurry, primary due to its high ash content and lower ash fusion temperatures. The composition of the constituents in the ash does not indicate the preferential deposition of any component in a single area of the turbine. These material balances indicated that the Beulah-Zap lignite fuel had a much higher deposition potential, as demonstrated by high levels (approximately 70 wt%) of ash recovered in the combustor. The Kemmerer also showed higher deposition levels than the Otisca fuel with approximately 12 to 13 wt% of the ash being retained in the combustor. With the Otisca fuel combustion tests, approximately 8 wt% of the ash was retained in the combustor while over 40 wt% of the Otisca fly ash was recovered in the cyclone pot. This is probably the result of the cyclone ash containing high levels of carbon (60% or greater), thus a large percentage of the fine mineral grains is still tied up in the char cenospheres and has not been released from the char particle where it could contact internal surfaces to form deposits. In addition, the agglomerating nature of the bituminous fuel tends to increase the efficiency of the cyclone on the exhaust of the turbine simulator, thereby collecting a higher percentage of particulate entering the cyclone.

An existing pressure vessel has been modified to include observation ports to perform atomization studies under typical turbine operating pressures and air flows. The main objective of this work is to determine if differences in atomization quality account for the improvements in carbon burnout experienced with the LRC fuels. The design of the spray chamber involves an existing 11.25-inch ID pressure vessel which has been modified to provide optical access perpendicular to the direction of the atomized spray. The optical access consists of two diametrically opposed 3-inch sight ports for the use of high-speed photography. In addition, a 2-inch sight port, opposite of a 1-inch national pipe thread port through which a sight pipe can be inserted, has also been added. The use of a sight pipe reduces the length of the spray which the Malvern 2600's laser beam must pass through and eliminates the potential for vignetting, which could occur if the beam were to pass through the complete spray cone. A honeycomb catalyst support is used as a flow straightener to provide a laminar flow of air around the atomizing nozzle. The height of the atomizer in relation to the optical ports is adjustable from outside the pressure vessel, thus allowing the atomizer position to be changed during a single atomization test.

Atomization testing was completed using a HWD Creek CWF with the Delavan 1.0-gal/min Swirl Air nozzle. This is the nozzle utilized during most of the combustion tests on the 1-MM Btu/hr gas turbine simulator. However, problems with a flat spray structure were encountered. A switch to the Delavan 2.5-gal/min nozzle, which has a larger orifice, gave acceptable performance at the expense of a lower than desired pressure ratio. Figure 4 shows the corrected Sauter mean diameter (SMD) for the three CWF atomized in the pressurized spray chamber. This figure indicates that the two HWD subbituminous CWFs atomized significantly better than the Otisca Industries produced Taggart seam bituminous CWF. This presumably is due to dilatant flow behavior of the Otisca CWF as compared to the pseudoplastic flow behavior of the HWD subbituminous CWF. The baseline water tests provided the best atomization behavior.

The emergence of advanced coal combustion technologies, such as coal slurry fired gas turbines, requires fundamental knowledge of the fuel combustion processes at elevated pressures. Of critical importance is the basic combustion kinetics and the fate of coal mineral matter in such systems. To address these issues, a pressurized drop-tube furnace (PDTF) was constructed to provide a low-cost test apparatus for conducting coal mineral matter transformation studies, deposition, burnout testing, and hot-gas cleanup studies under more controlled conditions. The PDTF is capable of operating under the following conditions:

Temperature: ambient to 2732°F (1500°C)
Pressure: ambient to 300 psia (20.4 atm.)
Oxygen: 0 to 20 mol%
Gas Flow: 0 to 7.8 scfm (220 L/min)
Residence Time: 0 to 5.0 sec

A multipurpose sampling probe with provision for char and fly ash collection or for collecting ash deposits on a cooled substrate is available. A detailed description of the PDTF system is given in Swanson and others (16).

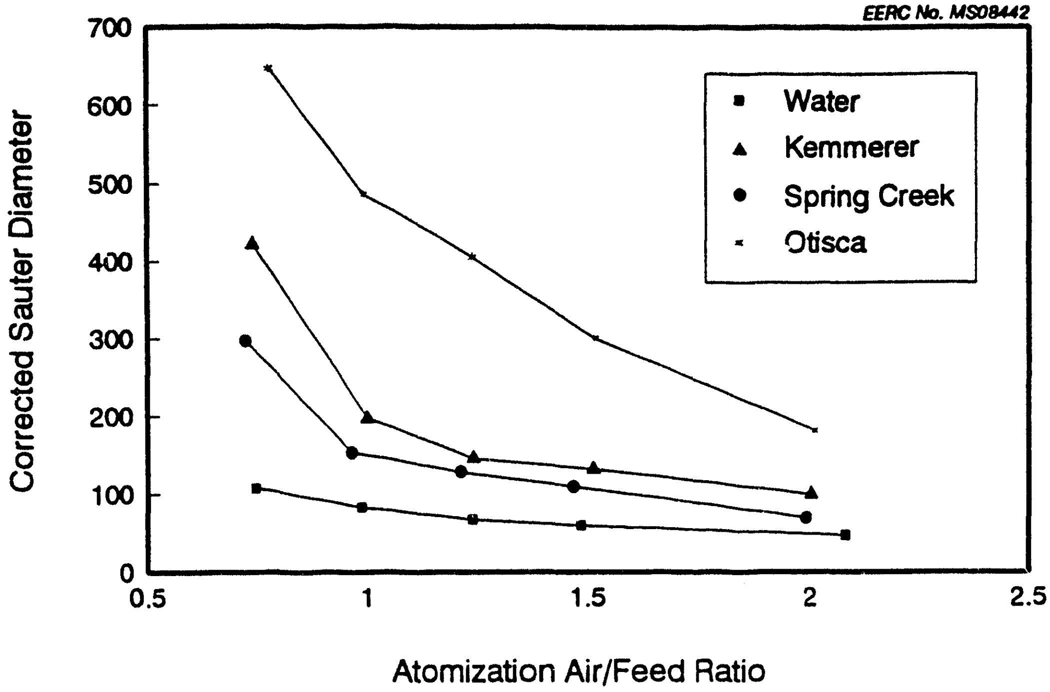

Figure 4. Corrected SMD as a function of atomizing air-to-fuel ratio for tested CWFs and baseline water.

Three scanning electron microscope/electron microprobe analysis (SEM/EMPA) techniques--computer-controlled scanning electron microscopy (CCSEM), scanning electron microscopy point count (SEMPC), and automated image analysis (AIA)--are presently used in ash behavior in combustion and gasification systems research at EERC. These techniques permit the study of transformations of inorganic constituents from the initial stages of coal conversion through the transformations that occur during ash deposition and slag formation. Their specific applications include 1) determination of the size, composition, and association of minerals in coals; 2) determination of the size and composition of intermediate ash components and fly ash; 3) determination of the degree of interaction (sintering) in ash deposits; and 4) identification and quantification of the components of ash deposits and slags; this includes liquid-phase composition, reactivity, and rystallinity.

Deposition testing of LRC fuels in the PDTF allowed the sticking fractions to be calculated for the tested fuels. These tests were all run at residence times of approximately 700 ms, gas temperatures of 1150°C, substrate temperatures of 900°C, and gas velocities through the accelerator of approximately 850 ft/s. These sticking fractions were ranked in the order PC/AC/HWD Beulah-Zap > PC/AC/HWD Spring Creek > HWD Spring Creek Allison fuel > Otisca Taggart > AC/HWD Kemmerer. Analysis of the deposits indicates that the Otisca fuel concentrated aluminum in the deposit. In the Kemmerer fuel deposit, a large increase in the concentration of calcium and sodium was observed in the deposit. The large increase in the calcium is due to the presence of calcium aluminosilicates in the coal ash which were not removed during the acid-cleaning process. The ash chemistry of the PC/AC/HWD Spring Creek fuel did not show any small significant increase in the concentration of any species in the deposits. The HWD Spring Creek fuel prepared for the Allison Gas Turbine Division showed a significant increase in the concentration of calcium and aluminum in the deposit, again probably due to the presence of lower melting calcium aluminosilicates and a significant decrease in the concentration of sodium in the deposit, as compared to the coal ash, probably due to the formation of volatile sodium species which did not impact and deposit on the deposition substrate. While the subbituminous fuel's ash chemistry was dominated by the formation of lower melting calcium aluminosilicates, the Beulah-Zap lignite ash chemistry was dominated by the low-melting-iron phases which can be attributed to residual magnetite left on the coal from the heavy-media physical cleaning process.

The fly ash combustion tests using beneficiated LRCs were conducted in the PDTF at 1300°C, 120 psia, and with a calculated residence time of 2.5 seconds. These high-pressure tests utilized Cyclones 2 and 5 from a multicyclone set and a final filter to collect the fine aerosols. The multicyclones were calculated to have cut points of 3.0 and 0.45 μm, respectively. Percent ash of the fly ash was determined using a modified thermogravimetric analysis (TGA) technique. Residence times are calculated based on center-line velocities equal to two times the plug-flow velocities.

Both the PC/AC/HWD/micronized and the Allison HWD/micronized Spring Creek fuels had lower sodium levels in the final filter fraction than the raw Spring Creek fuel. This is expected since acid-cleaning and HWD processes have been shown to reduce the sodium levels of the coal ash. However, the data indicates that for the hydrothermally treated fuel approximately the same percentage of the total sodium collected was recovered in the smallest-size fraction as was recovered with the as-received Spring Creek fuel. This data also indicates that acid cleaning of the fuel resulted in a significant decrease in the percentage of the sodium collected in the smallest-size fraction. A definite decrease in the amount of sodium recovered as submicron sodium sulfate or chloride aerosols on the final filter was observed with decreased sodium levels in the coal ash. This decrease indicates that benefication techniques such as acid cleaning and hot-water drying can substantially decrease the formation of the vapor-phase alkali species which participate in alkali sulfate induced deposition and corrosion of turbine blade materials in a direct coal-fired gas turbine.

Particle-size analysis of the three sized fractions was also conducted by SEM. These analyses indicate that the filter cake consists of very fine (<1 μm) particles while Cyclone 5 consisted of particles in the 1- to 4-μm size range and Cyclone 2 consisted of the larger particle sizes.

Tests of kaolin as an entrained alkali getter in atmospheric and pressurized coal combustion systems were performed in the EERC PDTF system. The kaolin powder was mixed with pulverized coal from the Spring Creek mine in the ratio of 1 part kaolin to 2 parts ASTM coal ash. Four combustion tests were performed at gas temperatures of 1500°C in the main furnace and between 1000° and 1100°C at the sampling point, with residence times of approximately 2 seconds; one test each of raw Spring Creek at atmospheric pressure, coal plus kaolin at atmospheric, raw coal at 100 psi, and coal plus kaolin at 100 psi. The results from the alkali gettering tests suggest that sodium is shifted strongly away from the smallest particles by the addition of kaolin. If we assume that the sodium sulfate in the smallest-size fraction formed when the gas was quenched during collection, then one half of the sodium was removed from the gas phase due to the kaolin addition. This result holds both at atmospheric and higher pressure. Most of the sodium was shifted to the 1- to 10-micron size range, which is where the kaolin is concentrated. The shift in sulfur from the smallest- to the largest-size ranges indicates that the sodium was chemically combined with the kaolin, probably in the high-temperature zone, and that the kaolin did not merely serve as a condensation surface for sodium sulfate. Because much of the sodium was removed from the gas phase, the sulfur shifted to the largest-size range by sulfating additional quantities of the calcium-rich particles.

4.0 CONCLUSIONS

General conclusions which can be drawn from the data presented in this report are as follows:

- Several production runs of LRC CWF were produced in conjunction with the DOE LRC beneficiation program at the EERC.

- By hot-water drying, high moisture coals can produce CWFs with heating values equal to or greater than their parent coals.

- Coal-water fuels from HWD LRCs have exhibited excellent rheological properties, which greatly benefit the fuel in areas of overall handling performance and long-range transportation.

- High-shear results indicated that the flow behavior of Spring Creek CWF does not change significantly, even at shear rates as high as 200,000 sec^{-1}, and with adjustments in solids loading.

- Detailed chemical and mineralogic analyses for the raw and hydrothermally treated coal revealed that most of the salts of organic acid groups and soluble minerals are removed by the beneficiation process.

- A pressurized combustion vessel was successfully built to allow the operating parameters of a direct-fired gas turbine combustor to be simulated.

- Seventeen successful combustion tests using CWFs were completed in the pressurized combustion vessel. These tests included seven tests with a commercially available Otisca Industries-produced Taggart seam bituminous fuel and five tests each with a physically and chemically cleaned Beulah-Zap lignite and a chemically cleaned Kemmerer subbituminous fuel.

- Analyses of the emission and fly ash samples highlighted the superior burnout experienced by the LRC fuels as compared to the bituminous fuel even under a longer residence time profile for the bituminous fuel. The LRC fuels have high-carbon burnouts, ranging from 98.2 to 99.99%, and appear to be relatively unaffected by other operating parameters; however, the bituminous fuel was significantly affected by combustion air temperature, atomizing air-to-fuel ratio, and fuel firing rate.

- The LRC fly ash showed a decrease in particle size when compared to the starting fuel, while the bituminous fuel showed a increase in particle size when compared to the starting fuel. These particle-size analyses provide some evidence of LRCs nonagglomerating properties as compared to bituminous fuels.

- Ash material balances for the CWF combustion tests indicated that the Beulah-Zap lignite fuel had a much higher deposition rate than the Kemmerer subbituminous fuel and the Kemmerer fuel had higher deposition rates than the Otisca bituminous fuel.

- Atomization data indicates that the two HWD subbituminous CWFs atomized significantly better than the Otisca Industries-produced Taggart seam bituminous CWF, presumably due to the dilatant flow behavior of the Otisca CWF as compared to the the pseudoplastic flow behavior of the HWD subbituminous CWF.

- Deposition testing of LRC fuels in the PDTF allowed the sticking fractions to be calculated for selected fuels. These sticking fractions were ranked in the order PC/AC/HWD Beulah-Zap > PC/AC/HWD Spring Creek > HWD Spring Creek Allison fuel > Otisca Taggart > AC/HWD Kemmerer.

- Both the PC/AC/HWD/micronized and the Allison HWD/micronized Spring Creek fuels had lower sodium levels in the final filter fraction than the raw Spring Creek fuel. This decrease is due to the removal of significant quantities of sodium cations in the beneficiation process.

- Results from the alkali gettering tests suggest that sodium is shifted strongly away from the smallest particles by the addition of kaolin. If we assume that the sodium sulfate in the smallest-size fraction formed when the gas was quenched during collection, then one half of the sodium was removed from the gas phase due to the kaolin addition. Most of the sodium was shifted to the 1- to 10-micron size range, which is where the kaolin is concentrated. The shift in sulfur from the smallest- to the largest-size ranges indicates that the sodium was chemically combined with the kaolin, probably in the high-temperature zone, and that the kaolin did not merely serve as a condensation surface for sodium sulfate.

5.0 RECOMMENDATIONS

The ability of hot-gas cleanup techniques to control particulte and alkali emissions entering the expander of a gas turbine to acceptable levels are seen as the biggest obstacles in commercialization of direct coal-fired gas turbines. Recommendations for future work include hot-gas cleanup work on the PDTF and 1-MM Btu/hr gas turbine simulator as potential filters and particulate removal techniques become available. In addition, further alkali sampling and alkali gettering experiments could be conducted on the PDTF in order to obtain a better handle on the composition and phases of the vapor alkali species and to determine ways to control them in a high-temperature environment before entering the expander of a gas turbine.

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