

BARRIER ISSUES TO THE UTILIZATION OF BIOMASS

Semiannual Technical Progress Report

for the period October 1, 2001, through March 31, 2002

Prepared for:

AAD Document Control

National Energy Technology Laboratory
U.S. Department of Energy
PO Box 10940, MS 921-143
Pittsburgh, PA 15236-0940

Cooperative Agreement No. DE-FC26-00NT41014
Performance Monitor: Philip Goldberg

Prepared by:

Jay R. Gunderson
Bruce C. Folkedahl
Darren D. Schmidt
Greg F. Weber
Christopher J. Zygarlicke

Energy & Environmental Research Center
University of North Dakota
PO Box 9018
Grand Forks, ND 58202-9018

May 2002

DOE DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report is available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161; phone orders accepted at (703) 487-4650.

ACKNOWLEDGMENT

This report was prepared with the support of the U.S. Department of Energy (DOE) National Energy Technology Laboratory Cooperative Agreement No. DE-FC26-00NT41014. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors(s) and do not necessarily reflect the views of DOE.

EERC DISCLAIMER

LEGAL NOTICE This research report was prepared by the Energy & Environmental Research Center (EERC), an agency of the University of North Dakota, as an account of work sponsored by DOE. Because of the research nature of the work performed, neither the EERC nor any of its employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement or recommendation by the EERC.

BARRIER ISSUES TO THE UTILIZATION OF BIOMASS

ABSTRACT

The Energy & Environmental Research Center (EERC) is conducting a project to examine the fundamental issues limiting the use of biomass in small industrial steam/power systems in order to increase the future use of this valuable domestic resource. Specifically, the EERC is attempting to elucidate the ash-related problems—grate clinkering and heat exchange surface fouling—associated with cofiring coal and biomass in grate-fired systems. Utilization of biomass in stoker boilers designed for coal can be a cause of concern for boiler operators. Boilers that were designed for low-volatile fuels with lower reactivities can experience damaging fouling when switched to higher-volatile and more reactive lower-rank fuels, such as when cofiring biomass. Higher heat release rates at the grate can cause more clinkering or slagging at the grate because of higher temperatures. Combustion and loss of volatile matter can start too early with biomass fuels compared to design fuel, vaporizing alkali and chlorides which then condense on rear walls and heat exchange tube banks in the convective pass of the boiler, causing noticeable increases in fouling. In addition, stoker-fired boilers that switch to biomass blends may encounter new chemical species such as potassium sulfates and various chlorides in combination with different flue gas temperatures because of changes in fuel heating value, which can adversely affect ash deposition behavior.

The goal of this project is to identify the primary ash mechanisms related to grate clinkering and heat exchange surface fouling associated with cofiring coal and biomass—specifically wood and agricultural residuals—in grate-fired systems, leading to future mitigation of these problems. The specific technical objectives of the project are:

- Modification of an existing EERC pilot-scale combustion system to simulate a grate-fired system.
- Verification testing of the simulator.
- Laboratory-scale testing and fuel characterization to determine ash formation and potential fouling mechanisms and to optimize activities in the modified pilot-scale system.
- Pilot-scale testing in the grate-fired system. The resulting data will be used to elucidate ash-related problems during biomass–coal cofiring and offer a range of potential solutions.

This multitask (Tasks 1 through 5) project began in October 2000 and is scheduled to be completed in June 2002. Task 1 involved the preparation of a Project Plan for review and approval by the Contracting Officer's Representative (COR). Based on COR approval of the Project Plan, Task 2, Modification of Pilot-Scale Combustion System, was initiated in January 2001. This task involved modification of an existing pilot-scale pulverized coal (pc)-fired combustion system to permit its use in a grate-fired configuration without preventing its future operation in an entrained firing configuration. Other Task 2 activities included upgrading of flue gas instrumentation supporting the pilot-scale combustion system as well as upgrades to the EERC's biomass fuel

preparation and storage capabilities. Task 2 activities are essentially complete, with completion of a few minor activities anticipated in May or June 2002.

Task 3, Verification Testing of the Simulator, began in December 2001 and was completed in January 2002. The pilot-scale grate-fired simulator was subjected to verification testing to ensure the modified system (fuel preparation and feed, combustor, and flue gas analyzers) operated as intended and its relevance to full-scale systems. Fuels were selected for verification testing based on the EERC's knowledge of full-scale grate-fired system performance and planned pilot-scale tests in Task 5. Data generated included combustion airflow rates, process temperatures, grate ash properties, fly ash properties, and flue gas properties. Based on the shakedown tests, the grate was modified and water cooling was added to the grate area to minimize clinker formation. Data generated during the verification tests will be summarized along with the Task 5 data in order to benefit the overall goal of the project in elucidating ash problems.

Task 4, Laboratory-Scale Testing and Fuel Characterization, involved fuel characterization and laboratory-scale combustion testing of coal and biomass parent fuels and coal-biomass blends to define key combustion and ash behavior issues to monitor during pilot-scale combustion testing. Laboratory testing was carried out in the combustion and environmental process simulator (CEPS) in order to allow for the testing of a wider range of fuels at a lower cost. The CEPS is a modular system capable of producing gas and particulate samples for analysis to elucidate ash transformation and deposition mechanisms but does not simulate the exact geometry of a full-scale boiler.

Based on the results of the laboratory-scale work, two separate biomass-cofired tests were completed for Task 5, Pilot-Scale Testing and Reporting, using the pilot-scale grate-fired system. Each test included a full suite of gas sampling, ash sampling, and deposit sampling similar to that performed in the laboratory-scale testing. Each of the two biomass fuels selected, wood chips and sunflower hulls, were fired at nominally 40 wt% based on the Task 4 laboratory-scale testing. The results from the pilot-scale grate-fired system are being analyzed and compared to existing data for pc-fired simulation and existing full-scale data for grate-fired systems where possible. Task 5 pilot-scale grate-fired combustion tests were completed in February 2002 and sample analysis was completed in late March.

This semiannual technical progress report documents project activities and summarizes results for the period October 2001 through March 2002. The discussion addresses accomplishments specific to project activities for Tasks 2 through 5. Preparation of a final project report is under way. A draft report will be completed in May and submitted to the project COR for review and comment.

TABLE OF CONTENTS

LIST OF FIGURES	ii
LIST OF TABLES	ii
EXECUTIVE SUMMARY	iii
INTRODUCTION	1
U.S. Biomass Resources	3
Technical Issues of Biomass Combustion	7
Biomass Power Systems	8
SCOPE OF PROJECT	12
Task 1 – Project Management Plan	12
Task 2 – Modification of the Pilot-Scale Combustion System	12
Task 3 – Verification Testing of the Simulator	13
Task 4 – Laboratory-Scale Testing and Fuel Characterization	14
Task 5 – Pilot-Scale Testing and Reporting	15
ACCOMPLISHMENTS	16
Task 1 – Project Management Plan	16
Task 2 – Modification of Pilot-Scale Combustion System	16
Modifications to Pilot-Scale CTF	16
Fuel Storage and Preparation	19
Flue Gas Instrumentation and Data Acquisition System Upgrades	25
Task 3 – Verification Testing of the Simulator	25
Modifications to Pilot-Scale CTF	25
Fuel Storage and Preparation	26
Flue Gas Instrumentation and Data Acquisition System Upgrades	27
Task 4 – Laboratory-Scale Testing and Fuel Characterization	27
Task 5 – Pilot-Scale Testing and Reporting	30
CONCLUSIONS AND RECOMMENDATIONS	31
REFERENCES	32
LIST OF ACRONYMS AND ABBREVIATIONS	38
COMBUSTION TEST FACILITY EXPERIMENT OPERATION SPECIFICATION	Appendix A

LIST OF FIGURES

1	Location of agricultural and forest residues	4
2	Promising locations for biomass energy crops	4
3	CTF and auxiliary systems for pc firing	13
4	Illustration of components for the grate-fired system	18
5	Photographs of the grate-fired section added to the CTF	18
6	Photograph of the walking-floor semitrailer	20
7	Photograph of agricultural forage box	21
8	Photograph of hydraulic power unit	22
9	Photograph of the hammer mill, blower assembly, and product recovery cyclone	24
10	Photograph of the platform feeder	24

LIST OF TABLES

1	Biomass Subtypes	5
2	Fuel Characteristics Requiring Special Attention	8
3	Proximate and Ultimate Analysis of Fuels	28

BARRIER ISSUES TO THE UTILIZATION OF BIOMASS

EXECUTIVE SUMMARY

Introduction

The Energy & Environmental Research Center (EERC) is conducting a project to examine the fundamental issues limiting the use of biomass in small industrial steam/power systems in order to increase the future use of this valuable domestic resource. Specifically, the EERC is attempting to elucidate the ash-related problems—grate clinkering and heat exchange surface fouling—associated with cofiring coal and biomass in grate-fired systems. Utilization of biomass in stoker boilers designed for coal can be a cause of concern for boiler operators. Boilers that were designed for low-volatile fuels with lower reactivities can experience damaging fouling when switched to higher-volatile and more reactive lower-rank fuels, such as when cofiring biomass. Higher heat release rates at the grate can cause more clinkering or slagging at the grate because of higher temperatures. Combustion and loss of volatile matter can start too early for biomass fuels compared to design fuel, vaporizing alkali and chlorides which then condense on rear walls and heat exchange tube banks in the convective pass of the boiler, causing noticeable increases in fouling. In addition, stoker-fired boilers that switch to biomass blends may encounter new chemical species such as potassium sulfates and various chlorides in combination with different flue gas temperatures because of changes in fuel heating value, which can adversely affect ash deposition behavior.

The goal of this multitask (Tasks 1 through 5) project is to identify the primary ash mechanisms related to grate clinkering and heat exchange surface fouling associated with cofiring coal and biomass—specifically wood and agricultural residuals—in grate-fired systems, leading to future mitigation of these problems. The specific technical objectives of the project are:

- Modification of an existing EERC pilot-scale combustion system to simulate a grate-fired system.
- Verification testing of the simulator.
- Laboratory-scale testing and fuel characterization to determine ash formation and potential fouling mechanisms and to optimize activities in the modified pilot-scale system.
- Pilot-scale testing in the grate-fired system. The resulting data will be collected, analyzed, and reported to elucidate ash-related problems during biomass–coal cofiring and offer a range of potential solutions.

Approach

Task 1 – Project Management Plan

The purpose of Task 1 was the preparation of a detailed Project Plan as requested by the U.S. Department of Energy (DOE). Task 1 also involved the preparation of a Hazardous Substance Plan. Both documents were to be submitted to DOE for review within 60 days of contract initiation, and the format was specified in the contract.

Task 2 – Modification of the Pilot-Scale Combustion System

The EERC currently has several pilot-scale systems to simulate pulverized coal (pc) firing. These systems have been used to study biomass and coal–biomass cofiring. A significant limitation of existing systems is that they do not effectively simulate grate firing, as is necessary to understand and identify opportunities to mitigate problems in full-scale stoker facilities. The EERC's combustion test facility (CTF) was modified to simulate a grate-fired system. However, the modifications will permit the continued operation of the pilot-scale combustion system in an entrained firing configuration. The CTF is an upfired reactor (approximately 70 lb coal/hr) that contains an existing fouling probe bank to simulate convective surfaces and a particulate control system that permits the use of either an electrostatic precipitator or a pulse-jet fabric filter. The modifications to the system were designed to best simulate existing industrial systems. Design criteria for the modified system include firing rate, process temperatures, residence time of ash on the grate, time and temperature history of entrained ash, flue gas constituents, and carbon conversion efficiency. The design strategy employed utilized a fixed-grate system with an air distribution plenum, a reciprocating ram to move ash and fuel across the grate, and combustion air piping to support operation of overfire air ports.

In addition to modifications directly to the CTF combustor, modifications were made to the feed system, and new feed preparation and handling equipment was procured to facilitate preparation of fuels for the grate-fired system. Upgrades were also made to the flue gas instrumentation and data acquisition systems.

Task 3 – Verification Testing of the Simulator

The pilot-scale grate-fired simulator was subjected to verification testing to ensure the modified system (fuel preparation and feed, combustor, and flue gas analyzers) operated as intended and its relevance to full-scale systems. Fuels were selected for verification testing based on the EERC's knowledge of full-scale grate-fired system performance and fuel selection for Task 5. Data evaluated included process temperatures, air distribution, grate ash properties, fly ash properties, and flue gas properties. Modifications were made to the system based on shakedown test results.

Task 4 – Laboratory-Scale Testing and Fuel Characterization

Fuel characterization and laboratory-scale combustion testing were performed on coal and biomass parent fuels and on coal–biomass blends to define key combustion and ash behavior issues to monitor during pilot-scale combustion testing. Laboratory testing was carried out in the combustion and environmental process simulator (CEPS) in order to allow for the testing of a wider range of fuels at a lower cost. The CEPS is a modular system capable of producing gas and particulate samples for analysis to elucidate ash transformation and deposition mechanisms but does not simulate the exact geometry of a full-scale boiler.

To identify the components leading to grate clinkering and ash fouling in a blend, it is essential to first understand the properties of the parent fuels. One representative coal sample and two biomass fuels were selected for analysis and combustion testing. The coal is representative of common commercial use in regions where the selected biomass types are available. The coal and biomass fuels were selected for availability and either current use or the likelihood of future use in commercial applications. Final fuel selection as well as the rationale used in the fuel selection process were reviewed with the DOE Contracting Officer's Representative (COR).

All fuels were analyzed to fully characterize the inorganic and ash-forming constituents using conventional techniques and advanced techniques. The three parent fuels were submitted for analysis of particle size, bulk density, heating value, proximate–ultimate analysis, chlorine, and major ash chemistry (i.e., SiO_2 , Fe_2O_3 , etc.). Advanced fuel analysis using chemical fractionation (CHF) and computer-controlled scanning electron microscopy (CCSEM) were also performed. These latter analysis techniques give a detailed picture of the mineralogy and chemistry of the inorganic fuel constituents not possible with conventional analysis. The data obtained from the advanced and conventional fuel analyses were used as input for two predictive models or indices to evaluate fireside performance, the model termed Predictive Coal Quality Effects Screening Tool (PCQUEST), developed at the EERC, and the Facility for the Analysis of Chemical Thermodynamics (FACT) model. The PCQUEST and FACT models complement each other, together providing a reasonable prediction of relative fireside performance.

Task 5 – Pilot-Scale Testing and Reporting

Based on the results of the laboratory-scale work (Task 4), combustion tests were performed in the pilot-scale grate-fired system. Two separate tests were completed, with each test including a full suite of gas sampling, ash sampling, and deposit sampling similar to that performed in the laboratory-scale testing. Each of the two biomass fuels selected were blended at a level determined from the laboratory-scale testing. A detailed test plan was developed with input from the COR after the grate-fired system design and laboratory-scale testing were complete.

All of the results for the pilot-scale grate-fired system are being analyzed and compared to existing data for pc-fired simulation and existing full-scale data for grate-fired systems where possible. Mitigation measures will be proposed if severe ash deposition is observed, although additional testing of mitigation measures is not within the scope of this project.

Project accomplishments and problems have been and will continue to be documented in monthly status reports and semiannual technical progress reports, with all of the project results compiled in a final project report. A draft final project report will be prepared and submitted to the DOE COR for review and comment prior to the final project report being issued.

Results

Task 1 – Project Management Plan

A Project Management Plan, Milestone Plan and Milestone Log, and Hazardous Substance Plan were prepared and submitted to DOE on November 29, 2000. In response to these submissions, the COR authorized the EERC to begin work on Task 2 – Modification of Pilot-Scale Combustion System in mid-December 2000. However, the COR requested further discussion of fuel selection, fuel selection rationale, and the scope of work planned for Task 4 – Laboratory-Scale Testing and Fuel Characterization prior to authorizing the EERC to proceed with Task 4. In response to the COR's request, a revised Project Plan was completed and submitted to the COR for review on February 2, and COR approval was received on February 9, 2001. Task 1 activities were completed in March 2001 with the submission of the revised Project Plan to AAD Document Control.

Task 2 – Modification of Pilot-Scale Combustion System

Task 2 activities were initiated in late December 2000 in response to the COR's review of the Project Plan and authorization to proceed. Task 2 was divided into three general areas of activity: 1) modification of pilot-scale combustor and fuel feed system to permit operation in a grate-fired configuration, 2) biomass fuel storage and preparation capabilities, and 3) acquisition of new flue gas analyzers and data acquisition system upgrades supporting the pilot-scale combustor. Task 2 activities are essentially complete except for installation of software and hardware upgrades to the data acquisition system. Completion of these upgrades is anticipated in June 2002.

Modifications to Pilot-Scale CTF

Modifications to the CTF were necessary in order to facilitate its operation in a grate-fired configuration while maintaining its pc-firing capability. The CTF was selected for this modification because of an extensive existing ash deposition database resulting from the pc-firing of bituminous and subbituminous coal, lignite, petcoke, biomass fuels, and various fuel blends over the past 35 years.

Design work related to the modification of the pilot-scale combustor to permit its operation in a grate-fired configuration began in December 2000 and was essentially completed in June 2001. Specific design work related to grate geometry, properly sizing the grate area to match the firing rate of the combustion system, combustion air delivery and distribution, and fuel feed options relative to grate geometry and size. The final design resulted in a rectangular grate with a surface area of 0.12 m² (1.25 ft²) in order to match the grate size to the combustion system firing rate (nominally 0.58 kJ/hr, or 0.55 MMBtu/hr). The grate is simply a 0.64-cm (0.25-in.) 316 stainless steel plate with an open grate area of 3.43% based on 322 holes (0.396 cm, or 0.156 in.) drilled through the plate.

Changes to some of these details were made as a result of shakedown test observations and are documented in the Task 3 discussion.

The fixed-grate arrangement requires the use of a ram to periodically move fuel and ash across the grate. Ram actuation frequency and stroke length depend on the fuel properties and firing rate. The gravity flow fuel feed system makes use of a hopper/gate arrangement that permits the distribution of fuel on the fixed grate to a desired level for a given fuel particle size and heating value. Changes in fuel feed rate are made using a combination of adjustments to the elevation of the fuel gates and the operating frequency and stroke length of the ram over the fixed grate.

Primary combustion airflow to the grate is controlled and divided into four zones over the length of the grate, representing 18%, 30%, 28%, and 24% of the grate area, respectively, from front to back. Overfire air is injected through multiple opposing ports above the grate. Primary air and overfire air represent 80%–90% and 10%–20% of the total combustion air, respectively.

Fuel Storage and Preparation

The EERC has had storage, handling, and preparation equipment to effectively process and size coal for use in pilot-scale pulverized coal (pc)-fired systems as well as fluid-bed combustion systems and pilot-scale gasification systems for 30+ years. Selective use and minor adjustments to this equipment permitted the preparation of appropriately sized coal for use in the pilot-scale grate-fired system. However, capabilities were not adequate to store and process biomass. Therefore, the EERC evaluated options to address biomass storage and processing (drying and sizing) requirements in order to meet the needs of this project as well as anticipated future projects involving biomass.

Existing storage bunkers at the EERC were not appropriate for use with most biomass fuels because they were designed for coal. Because biomass has significantly different flow properties and bulk density, alternative storage options were reviewed. The EERC determined the best option was the acquisition of a used over-the-road transport trailer that could be adequately tarped with a “live” bottom discharge. As a result of conversations with U.S. Environmental Protection Agency (EPA) personnel in July 2000, the EERC found a used walking-floor semitrailer being offered by Research Triangle Institute (RTI). The trailer is a 1979 Budd Walking Floor Trailer (12-m, or 40-ft, tractor trailer) and had been used in support of an EPA biomass demonstration project. The gross load limit for the trailer is 30,900 kg (34 tons), with a net cargo weight limit of 21,800 kg (24 tons).

In addition to the walking-floor semitrailer, the EERC also elected to purchase a new agricultural forage box. The forage box will be used for storage of small quantities of biomass fuel. However, its primary use will be to transfer biomass fuel from storage to processing equipment. After discussions with forage box dealers and a review of specifications and quotes provided, the EERC elected to purchase a front–rear combination unload Badger forage box. The combination front–rear unload capability permits the EERC to select between a controlled discharge of forage box contents through the front cross conveyor or unloading of the entire contents of the forage box in a short period of time through a rear door. Running gear design limits the forage box capacity to 12,700 kg (14 tons) gross weight, with a net weight limit of 8200 kg (9 tons).

The EERC obtained an hydraulic power unit driven by a gasoline engine offered as surplus property by EPA. After completing engine repairs as well as a tune-up and replacement of hydraulic hoses and hydraulic couplings to match those on the walking-floor semitrailer and agricultural forage box, the EERC successfully demonstrated that the hydraulic power unit was capable of supporting hydraulic operation of the trailer and forage box.

Fuel preparation had to address two requirements: 1) the potential need to dry a given quantity of biomass and 2) the need to properly size the biomass for a given combustion or gasification system. The need to dry a given biomass in support of this project was believed to be a low priority. However, options were considered where a surface moisture-drying capability could be incorporated into the general biomass storage/transfer capabilities.

Proper fuel sizing at reasonable capacity was the highest priority with respect to fuel preparation for this project. However, acquisition of multiple pieces of equipment to address all aspects of fuel sizing was not necessary. Therefore, the EERC's primary objective for acquisition of fuel-sizing equipment addressed adequate capacity (227 to 454 kg/hr, or 500 to 1000 lb/hr) and size reduction capabilities to specifically match fuel size requirements for existing pilot-scale combustion and gasification systems. As a result, the EERC elected to procure a rebuilt Jacobson hammer mill, Model 556DF11 (direct drive 30-kW [40-hp 220/440-V] 3-phase explosion-proof motor powers the hammer mill). This hammer mill is a quick-change half-screen unit with the capability to discharge product through an outlet blower or gravity chute. Depending on the feed material type and size and desired product size, processing capacity should be 227 to 454 kg/hr (500 to 1000 lb/hr). A blower assembly and additional screens were purchased for the hammer mill. The blower assembly permits the product from the hammer mill to be efficiently recovered in a cyclone and collected in a hopper, with undersized material and dust collected in an existing dust control system.

A new platform feeder and conveyor were purchased to support operation of the hammer mill. The platform feeder was procured to primarily support the processing of large quantities (>454 kg, or 1000 lb) of low-density biomass (grass- or straw-type material and chipped wood) in the hammer mill at a controlled feed rate. The new conveyor purchased to support operation of the hammer mill is a portable unit intended to deliver biomass to the hammer mill from the platform feeder or other sources. A magnetic header roller was specified for the conveyor to minimize the potential for metal objects to be discharged into the hammer mill.

Biomass storage, handling, and processing capabilities at the EERC should be adequate to support future biomass pilot-scale combustion and gasification projects. Storage and handling capabilities may also effectively support small demonstration projects. The only exception would be bulk material drying beyond simply surface moisture.

Flue Gas Instrumentation and Data Acquisition System Upgrades

In addition to modifications directly to the pilot-scale CTF fuel feed system and combustor, the EERC elected to replace the flue gas conditioner and five flue gas analyzers as well as upgrade the data acquisition system. The new flue gas sample conditioner and flue gas analyzers for oxygen,

carbon monoxide, carbon dioxide, sulfur dioxide, and nitrogen species to support the operation of the modified pilot-scale combustion system began to arrive in May 2001, with the last instrument delivered in July. Details concerning these equipment items were documented in previous status reports and will be documented in the final project report. Therefore, no further discussion of these items is presented in this report. Upgrades to the data acquisition system are an ongoing activity that will be completed in June.

Task 3 – Verification Testing of the Simulator

Task 3 began in December 2001 and was completed in January 2002. Initial grate-fired system shakedown tests resulted in excessive ash clinkering on the grate. EERC personnel felt that the ash clinkers initiated along the refractory walls adjacent to the grate and propagated across the grate surface. Mitigation efforts included fabricating a new grate, adding water-cooled surfaces to the refractory walls adjacent to the grate, and adding two additional sight ports to improve the ability to observe and access the grate on-line.

The new grate design increased the number of effective air nozzles but reduced the nozzle diameter in order to maintain the percent open grate area (3.43%) desired. Hole diameters decreased from 0.396 cm (0.156 in.) to 0.239 cm (0.094 in.) and the number of holes increased from 322 to 837. Hole spacing within each row is now 1.572 cm (0.619 in.) on center, and row spacing is 0.785 cm (0.309 in.) on center. In addition, water-cooled tubing was added to the air plenum side of the grate to improve grate thermal protection. Fabrication of the new grate and installation of water-cooled surfaces and sight ports in the refractory walls were completed in mid-January followed by a shakedown test to verify that the modifications made had successfully mitigated the ash clinkering previously observed.

The modified pilot-scale combustion system can successfully be used in a grate-fired or pc-fired configuration. Future projects may want to consider further modifications to the biomass feed system supporting grate firing depending on the material type and feed rate. Biomass fuel particle size and process parameters should be carefully considered for each material type fired.

Operation of the hammer mill and support equipment has been limited. Processing kiln-dried hardwood scraps into wood chips resulted in a product rate of 227 kg/hr (500 lb/hr). Straw/grass-type biomass was also processed in the hammer mill but the small quantity of material processed did not lend itself to determination of a product mass rate. Softwood and straw/grass-type biomass should result in a product rate of at least 454 kg/hr (1000 lb/hr).

Task 4 – Laboratory-Scale Testing and Fuel Characterization

Task 4 activities were initiated in February 2001 following the COR's approval of the revised Project Plan. A draft report documenting Task 4 experimental activities and results was prepared and submitted to the project COR on October 10, 2001. Following review and comment by the project COR, the Task 4 report was finalized in January 2002 and will be used in the preparation of a final project report.

Characterization of the biomass samples showed a lower moisture and sulfur content than the coal but twice as much volatile matter. The fixed carbon for both the wood chips and the sunflower hulls was less than half of the Cordero Rojo coal. The sunflower hulls had 1.5 times the ash content as the coal, while the wood chips contained a very low percentage of ash, nearly an order of magnitude lower. Chlorine levels in the biomass fuels were an order of magnitude higher than the coal.

The inorganic distribution in the wood and coal is fairly similar, with the exception of the wood being enriched in alkali and alkaline-earth elements and the coal having a somewhat higher sulfur level. The sunflower hulls, on the other hand, contain significantly higher phosphorus and potassium than the coal, with almost 60 wt% potassium and 8 wt% phosphorus. The hulls have much less silica, alumina, and calcium compared to the coal and wood.

The CHF analysis of the biomass fuels indicated that the majority of the inorganic material found to be leachable by water and ammonium acetate is in water-soluble form rather than organically associated as in coals. Generally, these materials will be more reactive than coal minerals because of a smaller size range but less reactive than organically associated materials. Therefore, when firing biomass, these highly dispersed elements have a high propensity to interact with other minerals present as well as form very fine ash.

Entrained fly ash and deposits were obtained in the CEPS combustor for the parent coal and coal biomass blends of 80–20 coal–biomass and 60–40 coal biomass. Although more volatile or aerosol flue gas components are generated with the biomass blends, such as chlorides and sulfates of potassium, these fine components seem to agglomerate and actually show more coalescence in the fine $<10\text{ }\mu\text{m}$ ($<0.0004\text{ in.}$) fraction compared to the baseline coal. Particulate control should not be an issue with these blends.

The deposits were collected on removable cooled probes for analysis and determination of growth rates and deposit strength. The highest deposit growth rate was found for the parent coal fired without biomass. This deposit, however, had the lowest strength of any of the deposits generated. The highest-strength deposit was the 60–40 Cordero Rojo–sunflower hull blend, which also had the lowest growth rate. These observations are believed to be a function of ash particle-size distribution (PSD) as well as chemistry.

Overall, the 20% biomass blends do not appear to be a cause for concern with respect to ash deposition or corrosion. For the 40% biomass blends, higher chlorine content may create some longer-term corrosion problems, especially when the biomass is cofired with low-sulfur coals. Ash deposition as a function of deposit strength did increase for the 40% sunflower hull blend, and some caution may be required at this higher blend ratio.

The PCQUEST model predicts a higher propensity for high-temperature fouling and slagging with the sunflower hull blends and only a slightly higher propensity with the wood chip blends when compared to the coal. This is exactly what is seen in the experimentally derived deposit growth strength development. The tube erosion numbers are higher for the coal and are probably related to

the greater content of larger silicate particles. The rest of the predictive values are relatively the same for all of the fuels.

Predicted deposition rates do not reflect what was seen in the laboratory-scale combustion and deposition tests. The deposition rate for the biomass blends is predicted to be higher than that of the pure coal. This is exactly the opposite of what was seen in the deposition tests. This deposition rate formula was empirically derived for coal and obviously does not apply to coal–biomass blends.

Task 4 results and recommendations were used in the development of final test plans for the Task 5 pilot-scale combustion tests. Recommendations considered in the planning of pilot-scale grate-fired system shakedown tests and the two pilot-scale coal–biomass cofiring tests completed include the following:

- 1) Use Cordero Rojo subbituminous coal for shakedown tests documenting fouling and slagging characteristics as well as fine particulate concentrations and bulk flue gas composition (oxygen, carbon dioxide, carbon monoxide, sulfur dioxide, and nitrogen species).
- 2) For the two cofiring tests, use blend ratios of 40% biomass and 60% coal (40% sunflower hulls–60% Cordero Rojo coal and 40% wood chips–60% Cordero Rojo coal) to obtain data that would represent a worst-case scenario for practical biomass cofiring with respect to potential adverse ash impacts.
- 3) Cofiring tests should include fine particulate sizing analysis.
- 4) Special attention should be paid toward characterizing fine particulate to determine concentrations of potassium chlorides and sulfates and phosphates which may impact performance with respect to fouling and slagging as well as fine-particle emissions.

Task 5 – Pilot-Scale Testing and Reporting

Task 5 activities during this reporting period included preparation of project reports as well as the completion of two pilot-scale coal–biomass cofiring tests. The pilot-scale testing component of this task began in January 2002 following the completion of Task 3. Task 5 pilot-scale tests were completed in February 2002, followed by sample analyses completed in March. Work on a draft final project report began in March, and the EERC expects to submit the draft report to the project COR for review in May 2002.

A draft test plan was prepared in December 2001 for the pilot-scale biomass cofiring tests and submitted to the project COR for review. The draft test plan was approved by the project COR during a telephone conversation in mid-December and was subsequently finalized. The first pilot-scale coal–biomass grate-fired combustion test was completed in late January 2002. This test involved cofiring a blend ratio of 40 wt% biomass (wood chips) and 60 wt% coal (Cordero Rojo subbituminous). The same blend ratio was used in early February for the second coal–biomass combustion test, cofiring sunflower hulls and Cordero Rojo subbituminous coal. Data evaluation is ongoing; therefore, results from these pilot-scale grate-fired tests are not available for inclusion in this report.

BARRIER ISSUES TO THE UTILIZATION OF BIOMASS

INTRODUCTION

Well over half of the electric generation in the United States is derived from coal. Many electric utilities that use coal for power generation are considering the use of renewable fuels such as waste products and energy crop-derived biomass fuels as a potential economical option for reducing greenhouse gas emissions. Calculations by the National Renewable Energy Laboratory (1) show that cofiring 15% and 5% by heat input of urban waste biomass with Illinois No. 6 coal reduces greenhouse gas emissions by 22% and 7%, respectively, on a CO₂-equivalent basis per unit of electricity produced. Therefore, biomass cofiring in coal-fired plants has the potential to significantly reduce greenhouse gas emissions. Questions arise as to the availability of biomass resources, modifications that may be necessary for existing plants, and the global greenhouse gas inventory. Therefore, the greatest potential for the utilization of biomass exists for smaller boilers used for heating and generation of process steam represented by older stoker-fired units and newer fluid-bed combustion units.

Some experts estimate that 14%–15% of total world energy consumption is already accounted for by biomass (2). Energy production from biomass fuel sources such as wood wastes, municipal wastes, agricultural wastes, and landfill or digester gases is currently only about 1% of the total U.S. output (3). However, recent projections show that production capacity could rise to 10% of the total U.S. output by the year 2010 (4), if more companies take on cofiring strategies and if dedicated sources of energy crops are produced (5). The European Union (EU), in response to the Kyoto Protocol, committed to reduce greenhouse gas emissions between 2008 and 2012 by 8% compared to 1990 levels. EU statistics show that currently about 2%–8% more CO₂ would be emitted within the EU without the current use of biomass (6). Estimates of remaining available solid biomass fuel potential indicate that a further reduction of CO₂ emissions of 7%–28% could be achieved.

The global inventory of greenhouse gas emissions remains a serious problem since many countries have little incentive to reduce greenhouse gas emissions. Treaties such as the Kyoto Protocol will hopefully create incentives. In the Netherlands, an additional incentive for the use of biomass wastes is the governmental policy to aim for a strong increase in renewable energy use (10% of the primary energy consumption in 2020, 4% from biomass and biomass wastes). Cofiring biomass and biomass waste streams with fossil fuels in large-scale power plants is considered to be an attractive option, since it benefits from the economy of scale and can potentially be realized at relatively low investment cost (7). If U.S. companies pursue biomass-cofiring opportunities in a manner comparable to European experience, biomass cofiring in the United States could have a significant impact on the global greenhouse gas pool.

Biomass types available for use as a cofiring fuel with coal fall into two major categories: biomass wastes and biomass energy crops. Waste products include wood wastes such as wooden pallets, telephone poles, sawdust and manufacturing scraps, and municipal solid wastes or sludge. Agricultural wastes may include peach pits; rice hulls; and straws of wheat, alfalfa, rape, timothy, and barley. Energy crops include fast-growing switchgrass and hybrid trees such as poplar and

willow. European research into direct firing and cofiring biomass with coal for power generation has been fairly extensive with various agricultural biomass fuels such as wheat straw and wood waste product fuels (8–13). In the United States, research has focused primarily on cofiring arrangements for wood (14–21), and more localized agricultural waste biomass fuels have been studied less intensely (22–26). A synopsis of biomass for energy production, written by European researchers, discussed issues and barriers to using biomass such as wood for energy production (27). Biomass combustion is summarized as having the following impacts: reduces greenhouse gases, decreases NO_x , destroys polychlorinated biphenyls, decreases smog, increases volatile organic compounds (greatly dependent upon combustion process), decreases CO , stimulates landscape and forest conservation, and reduces soil erosion if the wood source is from dedicated resources such as tree farms (27–28).

Biomass utilization by conventional coal-fired utilities will create some technical challenges (29). Design limitations of coal-fired boilers may also preclude the use of biomass beyond certain weight fractions of total fuel feed. Such limitations may include physical processing of the biomass for proper injection or feeding into the boiler. Other limitations include fireside performance of the biomass, including its impact on flame stability, boiler heat exchanger surface fouling or slagging, and corrosion. With respect to processing and feeding biomass, various utilities in Europe and the United States have developed size-reducing methods that facilitate feeding the more fibrous and pliable biomass fuel into the boiler, or in many cases, separate injection ports have been installed (8–9). Ash deposition and boiler tube corrosion can be an issue because biomass can contain considerable alkali and alkaline-earth elements and chlorine which, when mixed with other gas components derived from coal such as sulfur compounds, promote a different array of vapor and fine particulate deposition in a coal-fired boiler (8–10, 13, 24). Biomass can also contain organically deposited minerals such as amorphous silica phytoliths (30) which are difficult to characterize with standard coal analysis methods and which also behave differently than mineral silica forms such as quartz in coal. Initial assessments have been performed on the behavior of inorganic constituents of biomass during combustion (31) along with issues related to the cofiring of biomass–coal blends (32).

Utilization of biomass in stoker boilers designed for coal can be a cause of concern for boiler operators. Kautz determined that German boilers designed for low-volatile fuels with lower reactivities experienced damaging fouling when the boilers were switched to higher-volatile and more reactive lower-rank fuels, similar to what could be expected when firing biomass (33). Higher heat release rates at the grate caused more clinkering or slagging at the grate because of higher temperatures. Combustion and loss of volatiles essentially started too early for the lower-rank fuel compared to the design fuel, vaporizing alkali and chlorides which then condensed on rear walls and heat exchange tube banks in the convective pass of the stoker, causing noticeable increases in fouling. Williams et al. performed slagging and fouling assessments at three 17-MW stoker-fired boilers, focusing on the effects of furnace exit gas temperatures (FEGTs) on superheater fouling (34). Wood and almond shells were fired in the units, and higher rates of ash accumulation were noted for the higher-exit-temperature runs (maximum of 950°C , 1742°F) versus the lower-exit-temperature runs (maximum 800°C , 1472°F). Potassium sulfates and carbonates were increased in the deposits at the higher temperatures, but chlorides were very evident at the lower temperatures. These results are significant in that stoker-fired boilers that may switch to biomass blends may encounter new chemical species such as potassium sulfates and various chlorides in combination

with different flue gas temperatures because of changes in fuel heating value, which can adversely affect ash deposition behavior.

Frandsen et al. and Nielsen et al. studied ash deposition mechanisms for grate-fired boilers that had been converted from coal to straw fuel (35, 36). Findings included high concentrations of submicron aerosols for 100% straw combustion compared to coal–straw cofiring. Also, fly ash and ash-fouling deposits were produced which were very high in potassium chloride for 100% straw firing and much lower in chlorides for cofiring tests with coal because of interactions of potassium with coal silicates. Similar mechanisms of biomass combustion aerosol development were observed by Obernberger et al., and similar interactions between coal silicates and biomass chlorides and potassium compounds were reported by Folkedahl et al. and Zygarlicke et al. using simulated combustion testing to study the fundamentals of cofiring coal and wood, wheat straw, alfalfa stems, and rice straw lignin (37–44).

Stoker-fired boilers that cofire or switch to biomass fuel may potentially have to deal with ash behavior issues such as production of different concentrations and quantities of fine particulate or aerosols and ash-fouling deposition. Stoker boiler operators that are considering switching to biomass and adding potential infrastructure to accommodate the switch may also, at the same time, be looking into upgrades that will allow for generating additional power for sale on the grid.

U.S. Biomass Resources

In most U.S. locations, the availability of biomass as a fuel feedstock is not reliable beyond 20% of what is a normal firing rate for coal. Cofiring biomass up to 20%, therefore, is a practical application for incorporating a renewable energy fuel into a coal-fired plant. Figure 1 shows the location of current agricultural and forest activities where biomass resources are available in the form of residuals (45). Agricultural residuals are primarily available in the Midwest, Southeast, and mid-Atlantic regions, where there is a significant amount of farming activity. Forest resources and residuals are available in the New England, mid-Atlantic, Southeast, and upper Midwest regions as well as in the Pacific Northwest. Promising locations for various species of biomass energy crops are shown in Figure 2 (45).

Biomass has the potential to supply 24.7 EJ (23.5 quads) of energy for the United States, which represents approximately 28% of the U.S. energy consumption. This potential, as a function of the four major biomass categories, includes the following (46):

- Wood residuals – 3.7 EJ (3.5 quads)
- Agricultural residuals (from crops, food processing, and animals) – 1.7 EJ (1.6 quads)
- Dedicated energy crops – 17 EJ (16.1 quads)
- Urban wastes – 2.1 EJ (2.0 quads)

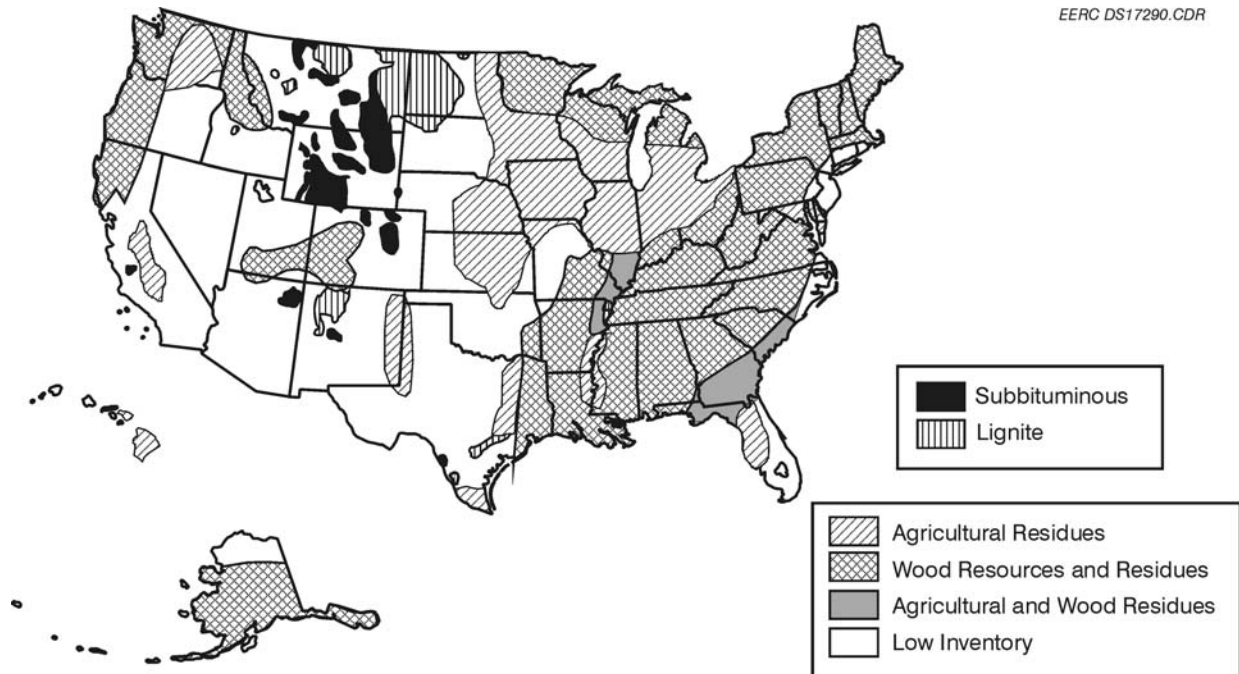


Figure 1. Location of agricultural and forest residues.

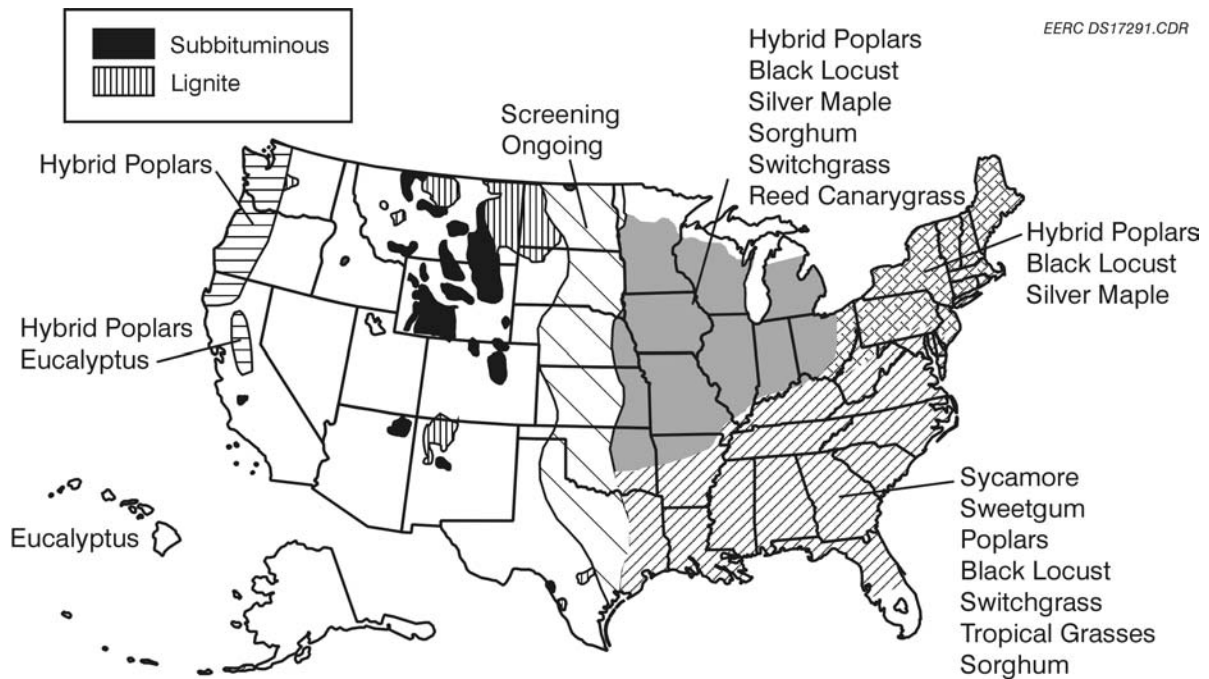


Figure 2. Promising locations for biomass energy crops.

The alternative fuels under each category that can be considered as a resource for cofiring are listed in Table 1. To some extent, all of these fuels are candidates for use in industrial and institutional stoker-fired combustion units. The availability of each resource, however, may be limited to certain areas. A study completed by Schmidt and Pinapati concluded that collectible quantities of biomass (excluding energy crops) totaled 7 EJ (6.65 quads) (47).

Table 1. Biomass Subtypes

Agriculture Based	Forest Products	Urban Wastes	Dedicated Energy Crops
<i>Harvest Residuals</i>	<i>Logging Residuals</i>	<i>Residential</i>	<i>Grasses</i>
Wheat Straw	Cull trees	MSW (municipal solid waste)	Switchgrass
Rice Straw	Tops	RDF (refuse-derived fuel) mixed paper	Native grasses
Flax Straw	Dead wood	Yard waste	
Cornstalks	Small-diameter stock	Demolition wood waste	
		Scrap tires	
<i>Processing Residuals</i>	<i>Primary Wood-Processing Residuals</i>	<i>Urban and Landscape Residue</i>	<i>Trees</i>
Rice Hulls	Sawdust	Leaves and grass clippings	Willow
Sugarcane Bagasse	Bark	Chipped and unchipped wood	Cottonwood
Almond Shells/Hull	Edgings	Construction and demolition waste	Hybrid poplar
Olive Pits	Slabs	Pallets/scrap	
Sugar Beet Pulp		Railroad ties	
Sunflower Hulls			
<i>Animal Wastes</i>	<i>Secondary Wood-Processing Residuals</i>		<i>Others</i>
Poultry Litter	Sawdust		Alfalfa stems
Feedlot Wastes	Edgings		Specialty crops

Large volumes of wood residuals are generated by the wood products industry, including paper mills, sawmills, and furniture manufacturing. While the wood products industry currently uses

much of its own residuals, there is still a substantial amount available, particularly from smaller sawmills that individually have too little waste wood to justify investing in steam or power production. In cases where a number of these smaller mills are in the same vicinity, a centrally located plant can purchase residuals from sawmills within an approximately 120-km (75-mile) radius to secure a supply of wood residuals sufficient to generate a significant amount of steam and/or power. Another significant source of wood residuals is forestry or “culls” from forest management (precommercial thinning of commercial forests, where dead, dying, or unmerchantable trees are selectively removed to increase the productivity of forests).

Wood residuals obtained from sound forest management do not deplete the net forest resource base. Through sustainable practices, either trees are replanted or the forest resource is managed for regeneration to enhance its health and productivity in the future. In some areas of the country, like the Tahoe Basin, forest management is essential to prevent major forest fires.

Agricultural residuals offer substantial energy resources for various applications. Crop residuals, processing residuals, and food-processing wastes are some components of the agricultural residual supply that can be used on-site or in regional facilities. Open-field burning of agricultural residuals was a common practice until recently, when the practice was banned in many locations because of air pollution concerns. Opportunities to use these residuals for fuel have been tempered, however, by a number of concerns related to their transport, handling, and impact on combustion system performance.

Dedicated energy crops, including short-rotation woody crops and herbaceous crops (primarily tall grasses such as switchgrass), represent the greatest potential source of biomass resources. Hybrid poplar and willow are two more common trees being studied for energy production. These trees will regrow vigorous shoots from the tree stumps that remain after harvesting, a form of regrowth that is known as coppicing. The resulting abundant new growth can then be harvested again in 5 to 10 years. The ability to obtain numerous harvests from a single planting significantly reduces average annual costs for establishing and managing energy crops.

Production of energy crops also requires much less intensive management than for most traditional agricultural crops, especially in terms of lower inputs of fertilizers and pesticides. In addition, because the root systems of energy crops remain in the ground between harvests, energy crops can help reduce soil erosion. The current cost of growing, harvesting, and transporting dedicated energy crops exceeds that of other “waste” biomass (as well as some fossil fuels), so subsidies of some sort or a mandatory percentage of biomass in the fuel mix will be required to promote near-term use of these materials.

MSW represents another significant source of biomass fuel. In the United States, paper and other organic materials typically represent a large portion of the waste stream—materials that make good combustion feedstock. Typically, 90% of the volume of MSW is combustible material. Other municipal and industrial wastes could also fuel an energy plant. Urban wood waste is another source of wood residuals, including tree trimmings, right-of-way and land clearance, waste wood from construction and demolition, broken wood pallets, fruit boxes, and other wood packaging.

Nonbiomass urban wastes, including sewage sludge, also represent potential sources of energy in urban areas.

Technical Issues of Biomass Combustion

The usable energy in biomass typically ranges from about 15,105 to 19,752 kJ/kg (6500 to 8500 Btu/lb) on a dry basis. However, biomass is generally not delivered dry. On a wet (green) basis, biomass typically has a moisture content of from 40% to 50%, which reduces the energy value of green hardwoods to about 9295–10,457 kJ/kg (4000–4500 Btu/lb). The moisture content of a single source of biomass fuel delivered to a plant can vary significantly because of differences in factors such as harvesting, storage, and drying conditions. Biomass with a heating value of <8133 kJ/kg (<3500 Btu/lb) would be of little value to a suspension-fired or grate-fired plant, since it would require a net energy input in order to sustain combustion.

Physical characteristics vary widely with biomass materials. For example, wood and grass have very different bulk densities. Non-woody biomass spans a much wider range of characteristics than woody biomass. The bulk density of woody material is generally in the range of 160–240 kg/m³ (10–15 lb/ft³). When biomass is densified by processing and compaction, its bulk density can be increased by 2 to 3 times. For example, the bulk volume of RDF, a processed form of MSW, is in the range of 400–433 kg/m³ (25–27 lb/ft³). By comparison, the bulk density of coal is approximately 721 kg/m³ (45 lb/ft³).

At the other end of the spectrum, agricultural materials such as loose straw can have a bulk density in the range of 16 to 40 kg/m³ (1 to 2.5 lb/ft³), although chopping or baling this type of material significantly increases its density. The tendency toward low weight per unit of volume translates into higher transportation costs. Thus options such as baling that keep the density higher for transportation purposes are especially important in considering the use of agricultural residuals (or herbaceous crops such as switchgrass). Their lower bulk density also means that special consideration must be given to handling and processing these materials as well as feeding them into combustion systems.

An important consideration for biomass is that the ash from some agricultural residuals and from new tree growth (e.g., the tops of trees or the ends of tree limbs) can have a relatively high alkaline metal content, particularly potassium and sodium. These alkaline metals tend to lower ash melting temperatures and can increase ash deposition and fouling of boiler equipment. Other ash constituents such as chlorine, silica phytoliths, and phosphorus can play a major role in developing ash deposits and fine particulate emissions. Special precautions like temperature control can be taken to limit fouling. However, there will be certain biomass materials that will only make an acceptable fuel when blended with other low-alkali biomass or coal in cofiring applications. Biomass materials high in silica, such as rice hulls, can cause erosion problems in the convective pass of the boiler; however, proper selection of gas velocities and selective use of refractory can minimize the erosion.

The inert materials, plastics, and various types of contaminants in municipal waste are a concern when using these materials to produce energy. Experience with separation and processing of municipal waste into RDF and cofiring in boilers has shown that RDF can be an acceptable fuel

for some boiler applications, especially fluid beds. Fluid-bed systems are much more forgiving of this “tramp” material than other combustion systems. Chlorine corrosion can be a concern with materials high in plastics.

The primary characteristics of biomass that require special attention when it is used as a fuel are summarized in Table 2. In all except the extreme cases, the stoker in combination with cofiring can be designed to deal with these troublesome characteristics.

Table 2. Fuel Characteristics Requiring Special Attention

Fuel Property	Troublesome Characteristics	Potential Problem	Proposed Solution
High Alkali (Na, K)	Formation of low-melting-point compounds	Slagging/fouling of convective surfaces	Low convective pass temperature (<1400°F) Sootblowing
		Sintering on the grate	Low firing temperature Fuel mixing (dilution)
Scrap Material	Accumulation of rock and metal	Plugging, mechanical breakdown	Tramp removal system
Rock	Glass and aluminum become molten	Sintering Convective pass fouling	Presorting Sootblowing
Dirt			
Metals			
Glass	Formation of alkali chlorides and HCl	Corrosion	On-grate chlorine capture Fuel mixing/dilution
Chlorine		Emissions exceeding local, state, or federal limits	Combustion air and temperature control
Bulk Density	Low bulk density	High transportation costs	Baling (compacting)
		High processing costs	Hydraulic ram feeder Fuel preparation

Biomass Power Systems

The characteristics of biomass power systems make it difficult for biomass to compete as a source of energy. The capital costs associated with biomass energy production are higher than those for conventional technologies, in part because of the extra emphasis that must be placed on fuel delivery and storage and handling systems and the higher costs associated with the reverse economies of scale for small systems. In addition to high capital costs (0.8 to 1.4 cents/MJ, or 3 to 5 cents/kWh), biomass systems typically have high fuel costs (0.6 to 1.1 cents/MJ, or 2 to 4 cents/kWh) and high operating and maintenance costs (0.8 to 1.4 cents/MJ, or 3 to 5 cents/kWh). The low efficiencies (<30%) of these systems also play an important role in keeping costs high.

Direct combustion of biomass for energy production was initially viewed as a suitable replacement for fossil fuels. Ash-related problems, including slagging, agglomeration, corrosion, and erosion, can cause frequent unscheduled shutdowns, decreasing the availability and reliability of this energy source. In addition, fouling of heat exchange surfaces coupled with the high moisture in the fuel reduces system efficiency. The variable nature of the quality of biomass fuel also impacts the reliability and availability of biomass systems.

The current status of the deregulated power industry has a significant impact on the introduction of new biomass power systems. The restructuring of the electricity market has shifted the focus from diversification of electricity-generating technologies to a least-cost approach to generating electricity. Deregulation-related barriers to the biomass industry include market prices, long-term capital investment risks, and inadequacies in alternative energy subsidies. The ability to command high prices for biomass-based power that was present under the Public Utility Regulatory Policy Act (PURPA) and other legislative actions has virtually disappeared, forcing biomass power to compete directly with other energy sources. In addition, the current transmission and dispatch market has not been developed to the point where a small, independent power producer can effectively negotiate a contract and cost-effectively sell power to the grid. Concerns over power quality also factor into the reluctance of the transmission companies to deal with small electricity producers.

Given the current status of biomass fuel options, utilization experience, and the market forces driving the utility and industrial sectors, an excellent near-term opportunity for biomass utilization within the United States is for biomass residuals and energy crops in small industrial-type boilers (commonly grate-fired systems). The primary technical hurdle is interaction of the inorganic components causing grate clinkering, heat exchange surface fouling, and fine particulate emissions. Other technical concerns relate to fuel handling and preparation.

Based on the literature cited and additional information gathered from personal communications with key biomass combustion experts, several key research focus areas pertaining to ash formation and deposition have been identified which relate to biomass cofiring in stoker or grate systems. Decisions concerning which pathway to pursue depend upon fuel selection. All of the experts commented that:

- There are serious heat-transfer and corrosion issues with respect to ash deposit formation and deposition in stoker or grate systems.
- Stokers are sensitive to the composition of the fuel in the same way as other boilers.
- A variety of general ash-related problems can plague stoker utilization of biomass, but types of fireside ash issues that can be anticipated are very dependent upon fuels or fuel blends. Fouling and slagging may not even be an issue for some biomass types, whereas corrosion or fine particulate control may be a main concern.

Discussions with Dr. Bryan Jenkins from the University of California-Davis (48), Drs. Ingwald Obernberger and Jonas Dahl from the University of Graz-Austria (49), Dr. Fleming

Frandsen from the Technical University of Denmark (50), and Dr. Jacob Kiel from the Energy Research Foundation of the Netherlands (51) related that stokers do indeed have serious heat-transfer and corrosion issues with respect to ash deposition. In general, as alkali and chlorine concentrations are increased, fouling and corrosion problems increase as well. Actual convective pass heat exchanger or fire-tube boiler fouling is more common for biomass fuels such as straws or grasses that have higher ash contents, along with significant concentrations of chlorine and potassium. The most widely used biomass fuel is wood. It is a well-known fact that wood fuels generally contain lower levels of sulfur, chlorine, and ash, compared to coal and most other biomass types. However, it is also known that severe corrosion of heat exchangers can occur in stokers burning wood. Ash deposition is not only the deposition of sticky or thick layers of insulating material that causes heat exchange problems, but also the deposition of fine particulate or vapor species through thermophoretic forces, vapor nucleation, condensation, chemical reaction, and agglomeration processes. These thin deposit layers can cause serious heat exchanger corrosion. Mitigation of ash deposition or corrosion problems can be proposed after deposit formation mechanisms are understood. In one case, University of Graz engineers proposed the reduction of combustion temperatures in a stoker system using flue gas recirculation in order to initiate sulfation of fly ash particles before the particle entered the convective pass. In situ sulfation of ash in the convective pass was leading to hard-to-remove ash deposits (52).

Discussions with Dr. Steve Benson from Microbeam Technologies Incorporated (53) revealed that managers of stoker systems who fire blends of U.S. subbituminous coals and biomass waste products from the pulp and paper industry have significant problems with the formation of ash clinkers on the grate and deposition on high-temperature refractory surfaces and convective pass surfaces. Based on their experience, managers have serious reservations concerning the cofiring of certain biomass types with their baseline coal. Experimental test burns of waste wood from the pulp and paper industry with a baseline Powder River Basin coal in a northern Minnesota stoker system showed a range of potassium–calcium aluminosilicate, sulfate, and some phosphate-based ash deposition throughout various temperature regions of the boiler beginning at the grate and moving through the convective pass. Carbonate-based deposits were identified in the electrostatic precipitators (ESPs) and hoppers. The types of ash deposition encountered were very dependent upon the temperature regime.

Discussions with Norman Hinman from BCI International (54) and Paul Wood and Marty McFadden from Ogden Power Pacific, Inc. (55), gave insight into the importance of understanding ash formation and deposition issues that could face stoker systems in California and other western states that would choose to burn forest-trimming woods and lignin fuels derived from wood or rice straw (lignin from ethanol production). Contacts all agreed that it cannot be assumed that stokers will perform adequately without any ash formation issues when new fuel types are being utilized in the boiler. Primary issues of concern were grate clinkering if high-silica lignin is used, fine-particle deposition of calcium silicates that could impede heat transfer, fine ash deposition of potassium chlorides that could cause severe corrosion, and the production of greater quantities of fines, which could cause emission violations.

Discussions with Larry Baxter from Brigham Young University (56) reiterated the importance of biomass and coal fuel types for ash issues that can be encountered in stoker systems. His

knowledge centered more on the development of NO_x with various configurations of air and fuel distribution around the grate and less on the complexity of ash interaction mechanisms. System parameters, including the distribution of air above and below the grate system, are critically important both for clinker deposit formation on the grate and ash fouling downstream. Imbalances in CO, O₂, and overall volatile yields can occur as below-grate air causes early drying and devolatilization of fuel, with the resulting gases carried upward and mixed later with above-grate air. This can result in insufficient mixing, significant unburned carbon, and localized reducing. Localized reducing can lead to lower-temperature melting points of ash and grate clinkering and tube fouling. In general, herbaceous biomass will result in more potential problems with respect to corrosion, ash deposition, and processing or feeding the biomass.

In an effort paralleling this project, the EERC has recently completed two projects funded by the U.S. Department of Energy (DOE) National Energy Technology Laboratory evaluating the feasibility of cofiring biomass in two stoker-fired boiler systems (57). The first project, entitled “Cofiring of Biomass at the University of North Dakota,” involved selection of a biomass fuel, completion of a biomass cofiring combustion test, an evaluation of plant modifications/upgrades required to enable biomass cofiring on a long-term basis, and preparation of an analysis addressing the economics of biomass cofiring (58). Biomass fuel selection was based on a resource assessment within a 100-mile radius of the University of North Dakota (UND). Fuel options identified included wood residues, sunflower hulls, and turkey manure. Sunflower hulls were determined to be the preferred fuel, resulting in combustion tests involving the cofiring of sunflower hulls and subbituminous coal. The maximum sunflower hull cofiring rate was 28 wt%. Results from the combustion tests demonstrated reductions in the emissions of sulfur dioxide and nitrogen species (nominally 15%), no increase in opacity was observed, and a small increase in boiler efficiency was observed. An assessment of plant modifications/upgrades determined that a nominal investment of \$400,000 and cofiring of 25% sunflower hulls would result in a \$100,000 annual savings in total fuel cost, resulting in a 5-year payback, or 20% return on investment.

The second project, entitled “Cofiring Biomass with Lignite Coal,” evaluated biomass cofiring with lignite in a small stoker system at the North Dakota State Penitentiary (59). A biomass resource assessment determined municipal wood residue to be the most viable fuel choice delivered at no cost. Free-delivered fuel resulted from an avoided \$10/ton landfill tipping fee. Fuel characterization and fireside modeling indicated ash clinkering and fouling would be minimal, and experimental combustion tests supported that conclusion. A technical and economic assessment addressing fuel-handling requirements and the addition of an electrical cogeneration capability determined that a 15- to 20-year return could be realized on a maximum investment of \$1,680,000. Fuel-handling requirements included bulk storage, general handling, sizing, segregation, and potential biomass drying. Electrical cogeneration and the resulting offset of current electrical costs were the most beneficial economic aspect. Other community economic benefits included avoided landfill burden (taxpayer costs), avoided tipping fees paid by waste generators, and additional employment opportunities at the North Dakota State Penitentiary associated with the biomass cofiring/cogeneration facility.

SCOPE OF PROJECT

The goal of this project is to identify the primary ash mechanisms related to grate clinkering and heat exchange surface fouling associated with cofiring coal and biomass—specifically wood and agricultural residuals—in grate-fired systems, leading to future mitigation of these problems. The specific technical objectives of the project are:

- Modification of an existing EERC pilot-scale combustion system to simulate a grate-fired system.
- Verification testing of the simulator.
- Laboratory-scale testing and fuel characterization to determine ash formation and potential fouling mechanisms and to optimize activities in the modified pilot-scale system.
- Pilot-scale testing in the grate-fired system. The resulting data will be collected, analyzed, and reported to elucidate ash-related problems during biomass–coal cofiring and offer a range of potential solutions.

Task 1 – Project Management Plan

The purpose of Task 1 was the preparation of a detailed project plan as requested by DOE. The project plan was to be submitted to DOE for review within 60 days of contract initiation, and the format was specified in the contract. Task 1 also involved the preparation of a Hazardous Substance Plan as requested in the contract. That document was also to be submitted to DOE within 60 days of contract initiation.

Task 2 – Modification of the Pilot-Scale Combustion System

The EERC has several pilot-scale systems to simulate pulverized coal (pc) firing. These systems have been used to study biomass and coal–biomass cofiring. A significant limitation of existing systems is that they did not effectively simulate grate firing, as is necessary to understand and identify opportunities to mitigate problems in full-scale stoker facilities. An existing EERC pilot-scale entrained combustion system was modified to simulate grate-fired operation. However, the modifications will not prevent future operation of the pilot-scale combustion system in an entrained firing configuration. Design criteria for the modified system included residence time of ash on the grate, time and temperature history of entrained ash, flue gas constituents, and conversion efficiency. System start-up was also a critical criterion in the design, since the grate-fired system required a modified approach to the conventional natural gas heatup for entrained system operation.

The EERC’s combustion test facility (CTF), illustrated in Figure 3, was modified to simulate a grate-fired system. The CTF is an upfired reactor (approximately 70 lb coal/hr) that contains an existing fouling probe bank to simulate convective surfaces and a particulate control system that permits the use of either an ESP or a pulse-jet fabric filter. The modifications to the system were

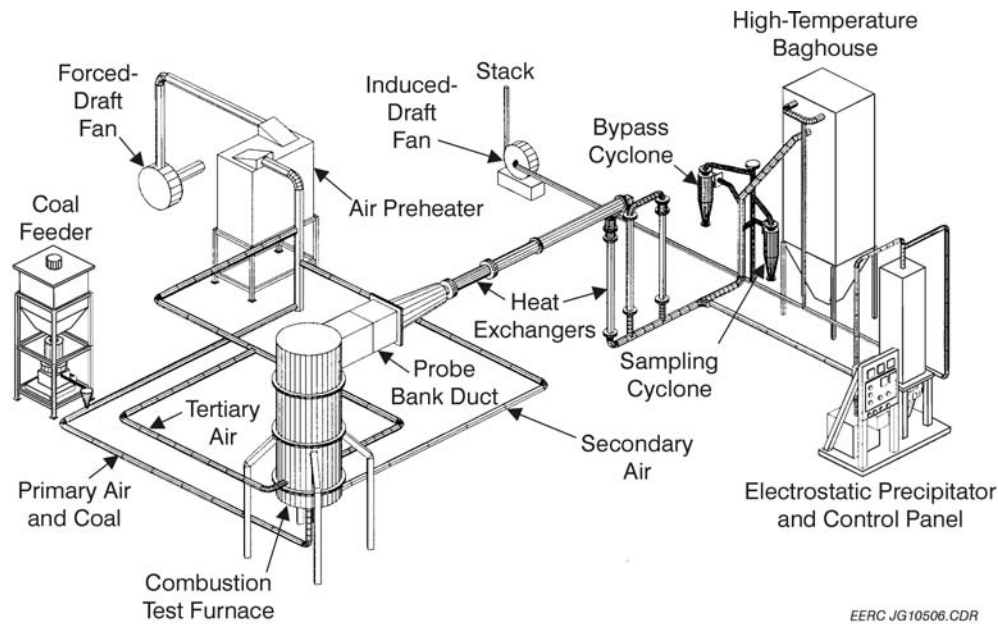


Figure 3. CTF and auxiliary systems for pc firing.

designed to best simulate existing industrial systems. The design strategy employed utilized a fixed-grate system with an air distribution plenum, a reciprocating ram to move ash and fuel across the grate, and new combustion air lines to support ports for overfire air.

In addition to modifications directly to the CTF combustor, modifications were made to the feed system, and new feed preparation and handling equipment was procured to facilitate preparation of fuels for the grate-fired system. Upgrades were also made to the flue gas instrumentation and data acquisition systems. New emission monitors purchased for the system include NO_x , SO_2 , O_2 , CO , and CO_2 analyzers as well as a new flue gas-conditioning unit.

Task 3 – Verification Testing of the Simulator

The pilot-scale grate-fired simulator was subjected to verification testing to ensure the modified system (fuel preparation and feed, combustor, and flue gas analyzers) operated as intended and its relevance to full-scale systems. Fuels were selected for verification testing based on the EERC's knowledge of full-scale grate-fired system performance fuel use planned for Task 5. Data developed include combustion process conditions, grate ash properties, fly ash properties, and flue gas properties. Adjustments were made to the system as necessary to mitigate performance deficiencies. The verification data generated as a result of shakedown tests completed will be summarized along with the Task 5 data in support of the overall goal of the project in elucidating ash problems.

Task 4 – Laboratory-Scale Testing and Fuel Characterization

Fuel characterization and laboratory-scale combustion testing were performed on coal and biomass parent fuels and on coal–biomass blends to define key combustion and ash behavior issues to monitor during larger pilot-scale combustion testing. Laboratory testing was carried out in the combustion and environmental process simulator (CEPS) in order to allow for the testing of a wider range of fuels at a lower cost. The CEPS is a modular system capable of producing gas and particulate samples for analysis to elucidate ash transformation and deposition mechanisms but does not simulate the exact geometry of a full-scale boiler.

To identify the components leading to grate clinkering and ash fouling in a blend, it is essential to first understand the properties of the parent fuels. One representative coal sample (Cordero Rojo subbituminous coal) and two biomass fuels (wood chips and sunflower hulls) were selected for analysis and combustion testing. The coal is representative of common commercial use in regions where the selected biomass types are available. The coal and biomass fuels were selected for availability and either current use or the likelihood of future use in commercial applications. Final fuel selection as well as the rationale used in the fuel selection process were reviewed with the DOE Contracting Officer's Representative (COR).

Experimental work focused on solving the ash-related problems of blending a coal with two biomass residuals (wood and sunflower hulls) local to a current or potential commercial application. All fuels were analyzed to fully characterize the inorganic and ash-forming constituents using conventional techniques and advanced techniques. The three parent fuels were submitted for analysis of particle size, bulk density, heating value, proximate–ultimate analysis, chlorine, and major ash chemistry (i.e., SiO_2 , Fe_2O_3 , etc.). Advanced fuel analysis using chemical fractionation (CHF) and computer-controlled scanning electron microscopy (CCSEM) were also performed. These latter analysis techniques give a detailed picture of the mineralogy and chemistry of the inorganic fuel constituents not possible with conventional analysis.

The data obtained from the advanced and conventional fuel analyses were used as input for two predictive models or indices to evaluate fireside performance. The model, termed Predictive Coal Quality Effects Screening Tool, or PCQUEST, was developed at the EERC and is designed to determine combustion performance indices, including the potential for furnace wall slagging and convective pass fouling of various fuels. PCQUEST is used to evaluate the relative performance of fuels and is most effective when compared to fuels of known fireside performance.

The Facility for the Analysis of Chemical Thermodynamics (FACT) model is an integrated thermodynamic database coupled to programs developed to calculate multicomponent multiphase equilibria based on a minimization of Gibbs' free energy. The code is used for assessing fuel quality effects on ash behavior in a boiler based on predictions of molar fractions (partial pressures) of all gas, liquid, and solid stable components. Output from FACT includes quantities, compositions, and viscosities of liquid and solid mineral phases; therefore, the code works well for predicting the behavior of fuel ash, including biomass-derived ash for different boiler temperature regimes. This model is especially useful for extrapolating to different temperature regions in a boiler to assess potential slag or fouling deposit formation, and it is also useful for performing blend evaluations.

The PCQUEST and FACT models complement each other, together providing a reasonable prediction of relative fireside performance.

These combustion tests, along with the fuel, deposit, and fly ash analysis results, provided insight into three key areas important to the cofiring of biomass–coal blends: 1) the overall combustion characteristics of the fuels and blends, 2) the characteristics of the inorganic material present in the fuels along with the transformation mechanisms that occur during ash formation and deposition, and 3) the effect of biomass–coal blending on the amount and size distribution of very fine particulate generated during combustion.

The information gained on ash formation and deposition mechanisms was used to optimize testing at the pilot scale. The resolution of any ash deposition problems, such as varied blend ratios to minimize deposition, added sootblowers, or alternate methods for stoker operation, will be addressed based on the results of the Task 5 pilot-scale grate-fired tests.

Task 5 – Pilot-Scale Testing and Reporting

Based on the results of the laboratory-scale work, testing was performed in the pilot-scale grate-fired system. Two separate tests were planned, with each test including a full suite of gas sampling, ash sampling, and deposit sampling similar to that performed in the laboratory-scale testing. Each of the two biomass fuels selected were blended at a level determined from the laboratory-scale testing, 60 wt% coal–40 wt% biomass. A detailed test plan was developed with input from DOE after the system design and laboratory-scale testing are complete.

All of the results from the pilot-scale grate-fired system were analyzed and compared to existing data for pc-fired simulation and existing full-scale data where possible. In addition to the technical assessment, an economic assessment will be summarized in the final project report based on separate ongoing activities and past projects at the EERC. Mitigation measures will be proposed if severe ash deposition is observed, although additional testing of mitigation measures is not within the scope of this project.

Project accomplishments and problems have been and will continue to be documented in monthly status reports. This document is the semiannual technical progress report for the period October 1, 2001, through March 31 2002. All of the project results are being compiled in a final project report. A draft final project report will be submitted to the DOE COR for review and comment in early May 2002 prior to the final project report being issued in June. A final project review meeting may be held at the National Energy Technology Laboratory (NETL) or at the EERC. Additionally, since biomass utilization is a rapidly growing topic, seven conferences were attended to acquire the latest biomass knowledge and to convey various project results to other researchers. Papers prepared for these conferences were submitted to the DOE COR for review and comment prior to their submission to the conference coordinator.

ACCOMPLISHMENTS

In February 2002, the EERC submitted a request for a 3-month, no-cost extension resulting in a project completion date of June 30, 2002. The reason for the request was ash-clinkering observed during coal-fired shakedown tests completed in December 2001, subsequent modifications made to the grate-fired system to mitigate the ash-clinkering problem, and the resulting delayed completion of two pilot-scale biomass cofiring tests planned for Task 5. The DOE Contracting Officer notified the EERC of approval of the request in a letter dated February 21, 2002. Project activities in the past 6 months have been limited to Task 2, Task 3, Task 4, and Task 5. The balance of this discussion will focus on accomplishments specific to project activities completed during the period October 2001 through March 2002.

Task 1 – Project Management Plan

Task 1 activities were completed in March 2001 with the distribution of the revised Project Plan approved by the COR. The revised Project Plan was submitted to AAD Document Control on March 16, 2001.

Task 2 – Modification of Pilot-Scale Combustion System

Task 2 activities were initiated in late December 2000 in response to the COR's review of the Project Plan and authorization to proceed. Task 2 was divided into three general areas of activity: 1) modification of pilot-scale combustor and fuel feed system to permit operation in a grate-fired configuration, 2) biomass fuel storage and preparation capabilities, and 3) acquisition of new flue gas analyzers to support the pilot-scale combustor. Task 2 activities are essentially complete except for installation of software and hardware upgrades to the data acquisition system supporting the pilot-scale combustion system modified to permit grate-firing. Completion of these upgrades is anticipated in June 2002.

Modifications to Pilot-Scale CTF

Modifications to the CTF were necessary in order to facilitate its operation in a grate-fired configuration while maintaining its pc-firing capability. The CTF was selected for this modification because of an extensive existing ash deposition database resulting from the pc-firing of bituminous and subbituminous coal, lignite, petcoke, biomass fuels, and various fuel blends over the past 35 years. As a result of the modifications made to facilitate grate firing, the only changes made involved fabricating a new bottom section for the combustor, combustion air piping, and the addition of a separate fuel feed system for grate firing.

Design work related to the modification of the pilot-scale combustor to permit its operation in a grate-fired configuration began in January 2001 and was essentially completed in June 2001. However, some limited design work continued on an intermittent basis in support of fabrication activities as well as modifications determined to be necessary as a function of system shakedown. Specific design work related to grate geometry, properly sizing the grate area to match the firing rate

of the combustion system, combustion air delivery and distribution, and fuel feed options relative to grate geometry and size.

The final design resulted in a rectangular grate with a surface area of 0.12 m^2 (1.25 ft^2), or $25 \times 46 \text{ cm}$ ($10 \times 18 \text{ in.}$) in order to match the grate size to the combustion system firing rate (nominally 0.58 kJ/hr , or 0.55 MMBtu/hr). The resulting grate area on a firing rate basis was $0.21 \text{ m}^2/\text{GJ}$ ($2.27 \text{ ft}^2/\text{MMBtu}$). The grate is simply 0.64 cm (0.25 in.) 316 stainless steel plate. Grate open area is 3.43% based on 322 holes (0.396 cm , or 0.156 in.) drilled through the plate in a 14-row triangular pattern. Hole positioning was 1.588 cm (0.625 in.) on center between rows and 1.98 cm (0.78 in.) on center within each row. Row spacing was 1.707 cm (0.672 in.) on center. Changes to some of these details made as a result of shakedown test observations are documented in the Task 3 discussion.

The fixed-grate arrangement requires the use of a ram to periodically move fuel and ash across the grate. Ram actuation frequency and stroke length depend on the fuel properties and firing rate. The gravity flow fuel feed system makes use of a hopper/gate arrangement that permits the distribution of fuel on the fixed grate to a desired level for a given fuel particle size and heating value. Changes in fuel feed rate are made using a combination of adjustments to the elevation of the fuel gates and the operating frequency and stroke length of the ram over the fixed grate.

Preparation of conceptual and fabrication drawings and material procurement began in April and June 2001, respectively. These activities were essentially completed in August 2001 except for updates required to document changes made as a result of shakedown tests. Fabrication of the components for the grate-fired system began in June and continued into January 2002, with modifications required based on shakedown test results. Figure 4 is an illustration of the grate-fired section added to the CTF. The fixed grate, ram, and fuel feed hoppers are indicated in the illustration. An ash collection area and access door for ash removal are also indicated. Primary combustion airflow to the grate is controlled and divided into four zones over the length of the grate representing 18%, 30%, 28%, and 24% of the grate area, respectively, from front to back. Overfire air is injected through multiple opposing ports about 71 cm (28 in.) above the grate but not shown in Figure 4. Primary air and overfire air represent 80%–90% and 10%–20% of the total combustion air, respectively. The refractory-lined combustor is preheated firing natural gas prior to initiating solid fuel firing.

Figure 5 is a photograph of the finished grate-fired system components installed on the CTF. The dark rust-colored section is the new CTF bottom, permitting grate firing. Specific items visible in the photograph include 1) fuel feed hoppers with sight windows to monitor fuel level, 2) the ram and actuator at the base of the fuel hoppers, 3) stainless steel flex hoses delivering preheated primary air to the grate plenum, 4) insulated headers delivering preheated overfire air above the grate, and 5) some of the doors that permit access to the ash collection area below the grate. Further modifications to this grate-fired system are likely in the future to improve performance and increase flexibility. However, any further modifications will be addressed within future projects. Detailed fabrication drawings of all components for the grate-fired system are maintained in a design file at the EERC.

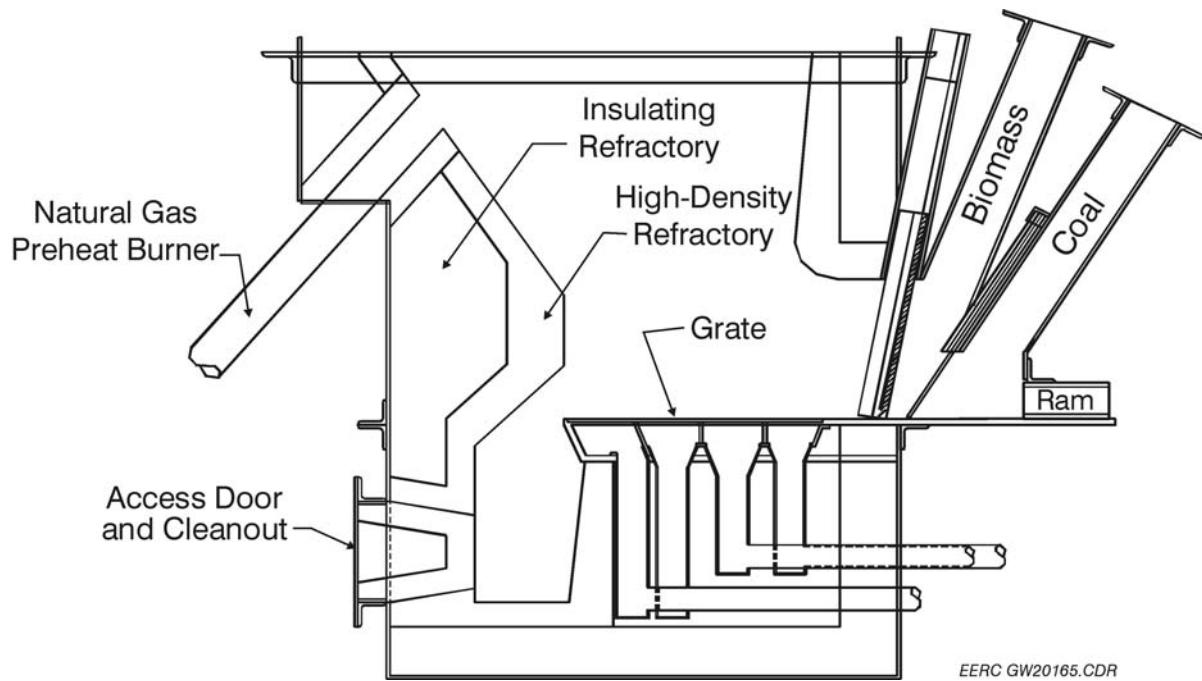


Figure 4. Illustration of components for the grate-fired system.



Figure 5. Photographs of the grate-fired section added to the CTF.

Fuel Storage and Preparation

The EERC has had storage, handling, and preparation equipment to effectively process and size coal for use in pilot-scale pc-fired systems as well as fluid-bed combustion systems and pilot-scale gasification systems for 30+ years. Selective use and minor adjustments to this equipment permitted the preparation of appropriately sized coal for use in the pilot-scale grate-fired system. However, capabilities were not adequate to store and process biomass. Therefore, the EERC evaluated options to address biomass storage and processing (drying and sizing) requirements in order to meet the needs of this project as well as anticipated future projects involving biomass. As a result, the EERC procured and installed new and used equipment items to meet biomass storage and processing requirements.

Existing storage bunkers at the EERC were not appropriate for use with most biomass fuels because they were designed for coal. Because biomass has significantly different flow properties and bulk density, alternative storage options were reviewed. Biomass storage criteria included a capacity of nominally 9000 to 18,000 kg (10 to 20 tons), with a “live” bottom capability to effectively transfer the material. To be effective, storage facilities must protect the biomass from the elements to avoid weathering or significant changes in surface moisture. The primary option that the EERC considered was the acquisition of a used over-the-road transport trailer that could be adequately tarped with a live bottom discharge. An over-the-road trailer could be used to pick up a quantity of biomass at a commercial site as well as meet on-site storage requirements.

Based on personnel experience, the EERC determined that the most flexible trailer storage option available was a walking floor-type trailer that could be tarped/covered. After reviewing new and used trailer options, the EERC determined that a new trailer was cost-prohibitive. As a result of conversations with U.S. Environmental Protection Agency (EPA) personnel in July 2000, the EERC found a used walking-floor semitrailer being offered by the Research Triangle Institute (RTI). The trailer is a 1979 Budd walking-floor trailer (12-m, or 40-ft, tractor trailer) that had been used in support of an EPA biomass demonstration project. The gross load limit for the trailer is 30,900 kg (34 tons), with a net cargo weight limit of 21,800 kg (24 tons). Nominal capacity on a volumetric basis is 72 m³ (2560 ft³). Assuming a material bulk density of 240 kg/m³ (15 lb/ft³), the capacity of the trailer would be nominally 17,000 kg (38,000 lb, or 19 tons). After several conversations with RTI and EPA personnel concerning the condition of the trailer, the EERC initiated a procurement action in order to obtain the used walking-floor semitrailer. Subsequent to its delivery in December 2001, the EERC had a new roll tarp installed on the trailer to protect contents from weather conditions. A photograph of the trailer is presented in Figure 6.

In addition to the walking-floor semitrailer, the EERC also elected to purchase an agricultural forage box. The forage box will be used for storage of small quantities of biomass fuel. However, its primary use will be to transfer biomass fuel from storage to processing equipment. After reviewing new and used forage box options with ten retail companies in the area, the EERC determined that a new forage box was the best option based on the poor condition of available used units. After further discussions with forage box dealers and a review of specifications and quotes provided, the EERC elected to purchase a 5.5-m/12,700 kg (18-ft/14-ton) front-rear combination



Figure 6. Photograph of the walking-floor semitrailer.

unload Badger forage box. The combination front/rear unload capability permits the EERC to select between a controlled discharge of forage box contents through the front cross-conveyor or unloading of the entire contents of the forage box in a short period of time through a rear door. The versatility offered by this arrangement is highly desirable when considering potential materials-handling and processing requirements.

Running gear design limits the forage box capacity to 12,700 kg (14 tons) gross weight, with a net weight limit of 8200 kg (9 tons). Nominal capacity on a volumetric basis is 23 m³ (800 ft³). Assuming a material bulk density of 240 kg/m³ (15 lb/ft³), the capacity of the trailer would be nominally 5450 kg (12,000 lb, or 6 tons). The EERC initiated procurement actions in August, and the forage box was delivered in September 2001. A photograph of the forage box is presented in Figure 7.

In order to properly site and facilitate the use of the walking-floor semitrailer and agricultural forage box, the EERC requested (September 2001) and DOE granted (October 2001) permission to install a concrete pad (nominally 60 by 70 ft, or 4200 ft²). In addition, the concrete pad will be used for air-drying biomass materials with high surface moisture when necessary prior to processing. Since the EERC was able to reduce anticipated expenditures as a result of acquiring several pieces of used equipment, the original equipment budget was adequate to cover the cost of installing the concrete pad. Separately, the EERC covered expenses incurred with respect to moving and protecting utilities at the location where the concrete pad was installed using internal funding. The concrete pad was poured in November 2001 and is visible in Figure 6.



Figure 7. Photograph of agricultural forage box.

In addition to the walking-floor semitrailer obtained from RTI, the EERC obtained other miscellaneous surplus equipment from EPA. A specific item of interest offered as surplus property by EPA was an hydraulic power unit driven by a gasoline engine. The EERC's interest in this piece of equipment stemmed from its potential to operate the hydraulic floor of the walking-floor semitrailer and the cross-conveyor and apron of the agricultural forage box. Typically, hydraulic power to operate the walking-floor semitrailer would be supplied by the semitractor towing the trailer. In the case of the agricultural forage box, a farm/industrial tractor would supply the necessary hydraulic power. Since the EERC does not own either a semitractor or a farm/industrial tractor, an alternative hydraulic power source was required. One option was adding a hydraulic pump to an existing EERC skid-steer loader. However, hydraulic fluid capacity would be limited.

In order to assess the potential to use the hydraulic power unit, acquired from EPA as surplus property, it was necessary to completely disassemble and clean the unit. The gasoline engine that drives the hydraulic pump required repairs as well as a tune-up. Engine repairs included replacing the fuel tank, throttle assembly, and governor gear. In addition, hydraulic hoses were replaced and hydraulic couplings were installed to match those on the walking-floor semitrailer and agricultural forage box. After completing this effort, the EERC successfully demonstrated that the hydraulic power unit was capable of supporting hydraulic operation of the trailer and forage box. Subsequently, a cart was purchased, and the components were mounted on the cart so that the hydraulic power unit could be easily moved to support operation of the trailer and forage box. Work on the hydraulic power unit was completed in January 2002. A photograph of the hydraulic power unit is presented in Figure 8.



Figure 8. Photograph of hydraulic power unit.

Fuel preparation had to address two requirements: 1) the potential need to dry a given quantity of biomass and 2) the need to properly size the biomass for a given combustion or gasification system. The need to dry a given biomass in support of this project was believed to be a low priority. However, options were considered where a surface moisture-drying capability could be incorporated into the general biomass storage/transfer capabilities. As a result, surface drying of biomass can be accomplished outdoors, assuming weather conditions are appropriate, by spreading the biomass on the poured concrete pad previously discussed and turning it over periodically to achieve a desired level of air drying. Another option is to continuously transfer the biomass between the walking-floor semitrailer to the agricultural forage box and back to the trailer until the desired surface moisture is achieved as a result of air drying. In the event of inclement weather, indoor air drying is also an option and will be discussed later.

Proper fuel sizing at reasonable capacity was the highest priority with respect to fuel preparation for this project. However, acquisition of multiple pieces of equipment to address all aspects of fuel sizing was not necessary. An existing rotary crusher and hammer mill can be used for some biomass fuel preparation activities involving small quantities (45 kg/hr, or 100 lb/hr) for pulverized fuel and some fluid-bed firing. The EERC can request permission to make use of a commercial wood chipper that is owned and operated by the city of Grand Forks. Also, a local business has a tub grinder available that the EERC can utilize for a fee. Therefore, the EERC's primary objective for acquisition of fuel-sizing equipment addressed adequate capacity (227 to 454 kg/hr, or 500 to 1000 lb/hr) and size reduction capabilities to specifically match fuel size requirements for existing pilot-scale combustion and gasification systems. Size reduction requirements included as small as 1.65 mm/1650 μ m to 0.63 cm (10 mesh/0.06 in. to 0.25 in.) material for pulverized fuel applications and 0.63 to 5.1 cm (0.25 to 2.0 in.) material for fluid-bed

and grate-fired applications, depending on the physical properties of the fuel and specific process conditions. To address this issue, the EERC developed an equipment specification addressing the size reduction and capacity requirements previously stated and reviewed the information with potential equipment suppliers. Final equipment selection was based on anticipated equipment performance, based on vendor information and EERC experience, as well as cost.

As a result of discussions with several potential equipment suppliers, the EERC elected to focus on the acquisition of an appropriately sized hammer mill, with multiple screens to affect product size, to achieve most biomass fuel preparation requirements. After reviewing options concerning new and used equipment, the EERC elected to procure a rebuilt Jacobson hammer mill, Model 556DF11. This hammer mill is a quick-change half-screen unit with the capability to discharge product through an outlet blower or gravity chute. Depending on the feed material type and size and desired product size, processing capacity should be 227 to 454 kg/hr (500 to 1000 lb/hr). A direct-drive 30-kW (40-hp 220/440-V) 3-phase explosion-proof motor powers the hammer mill. The rebuilt hammer mill was delivered in June, and performance processing of wood and straw material was evaluated during a brief test in July 2001.

Following delivery, inspection, and initial testing of the hammer mill, an order was placed with the hammer mill manufacturer for a blower assembly and additional screens. The blower assembly permits the product from the hammer mill to be efficiently recovered in a cyclone and collected in a hopper with undersized material and dust collected in an existing dust control system. Final installation of the hammer mill, product recovery piping, and dust control piping occurred in January 2002 following delivery of the blower assembly and piping components. A photograph of the hammer mill and product recovery cyclone is presented in Figure 9.

A new platform feeder and conveyor were purchased to support operation of the hammer mill. The platform feeder was procured to primarily support the processing of large quantities (>454 kg, or 1000 lb) of low-density biomass (grass- or straw-type material and chipped wood) in the hammer mill at a controlled feed rate. However, the platform feeder may have application for other biomass-handling requirements. Operated in conjunction with the agricultural forage box, the platform feeder can be used indoors to air-dry biomass by continuously transferring biomass between the platform feeder and the forage box and back to the platform feeder until the desired surface moisture level is achieved. Platform feeder dimensions are nominally 3 by 4.3 m (10 by 14 ft), with drag bars and dual beaters delivering material to a cross-conveyor. The cross-conveyor belt material is a 51-cm (20-in.) wide raised rib rubber with a fabric back. A 3.7-kW (5-hp/220-V) 3-phase explosion-proof motor and chain drive assembly powers the platform feeder and permits variable-speed unloading. The platform feeder was ordered in June and delivered in August 2001. Assembly of the platform feeder was completed in September, and a short operational test was successfully performed. Final installation of the platform feeder was completed in conjunction with the hammer mill. Figure 10 is a photograph of the platform feeder.



Figure 9. Photograph of the hammer mill, blower assembly, and product recovery cyclone.



Figure 10. Photograph of the platform feeder.

The new conveyor purchased to support operation of the hammer mill is a portable unit nominally 0.6 m (2 ft) wide and 4.6 m (15 ft) long, powered by a 1.1-kW (1.5-hp/230/460-V) 3-phase explosion-proof motor and gear drive. Belt material is a 0.6-m (2-ft), wide rubber z-top (Chevron) with fabric back. The elevation of the discharge end of the conveyor is adjustable to 1.8 m (6 ft) to simplify installation of the hammer mill and platform feeder and maximize the conveyor's versatility. A magnetic header roller was specified for the conveyor to minimize the potential for metal objects to be discharged into the hammer mill. The conveyor was procured to specifically deliver biomass to the hammer at a controlled rate. However, it may also have application for biomass transfer between the platform feeder and forage box for the purpose of biomass air drying. The conveyor was ordered in January and delivered in February 2002. Final installation, wiring, and testing of the conveyor were completed in February 2002. The conveyor can be seen, located between the platform feeder and hammer mill, in the Figure 9 photograph.

Flue Gas Instrumentation and Data Acquisition System Upgrades

In addition to modifications directly to the pilot-scale CTF fuel feed system and combustor, upgrades were also made to the flue gas instrumentation and data acquisition system. The flue gas conditioner and most of the flue gas analyzers supporting the CTF were more than 20 years old. As a result, reliability had deteriorated, maintenance costs were increasing, and spare parts were difficult to obtain if not discontinued. Hence, the age and condition of the equipment had the potential to affect flue gas data availability and quality. Therefore, the EERC elected to replace the flue gas conditioner and five flue gas analyzers as well as upgrade the data acquisition system.

The new flue gas sample conditioner and flue gas analyzers for oxygen, carbon monoxide, carbon dioxide, sulfur dioxide, and nitrogen species to support the operation of the modified pilot-scale combustion system began to arrive in May 2001, with the last instrument delivered in July. Details concerning these equipment items were documented in previous status reports and will be documented in the final project report. Therefore, no further discussion of these items is presented in this report.

Task 3 – Verification Testing of the Simulator

Modifications to Pilot-Scale CTF

Task 3 began in November 2001 and was completed in January 2002. Shakedown tests completed in December 2001 resulted in excessive ash clinkering on the grate. EERC personnel felt that the ash clinkers initiated along the refractory walls adjacent to the grate and propagated across the grate surface. As a result, some additional design work and fabrication drawings were necessary to make modifications to the grate area in order to minimize ash clinkering. Modifications included fabricating a new grate, adding water-cooled surfaces to the refractory walls adjacent to the grate, and adding two additional sight ports to improve the ability to observe and access the grate on-line.

The new grate design increased the number of effective air nozzles but reduced the nozzle diameter in order to maintain the percent open grate area (3.43%) desired. Hole diameters decreased

from 0.396 cm (0.156 in.) to 0.239 cm (0.094 in.) and the number of holes increased from 322 to 837. Hole spacing within each row is now 1.572 cm (0.619 in.) on center, and row spacing is 0.785 cm (0.309 in.) on center.

In addition, water-cooled tubing was added to the air plenum side of the grate to improve grate thermal protection. The design modifications were documented in revised fabrication drawings. Fabrication of the new grate and installation of water-cooled surfaces and sight ports in the refractory walls were completed in mid-January, followed by a shakedown test to verify that the modifications made had successfully mitigated the ash clinking previously observed. Data from the shakedown tests will be summarized along with the data generated as a result of the pilot-scale grate-fired biomass cofiring tests completed in Task 5.

Fuel Storage and Preparation

In order to address biomass storage and handling requirements, the EERC purchased a used walking-floor semitrailer and a new agricultural forage box. The used walking-floor semitrailer is a 1979 Budd walking-floor trailer (12-m, or 40-ft, tractor trailer). The new forage box is a 5.5-m/12,700-kg (18-ft/14-ton) front-rear combination unload Badger forage box. The performance of the walking-floor semitrailer and agricultural forage box was verified during short operability tests using a portable hydraulic system powered with a 7.5-kW (10-hp) gasoline engine. Specifically, the floor of the walking-floor semitrailer and the cross-conveyor and apron of the forage box were operated for nominally 30-minute periods. Both trailers were demonstrated to be road worthy as a result of their cross-country delivery.

Fuel preparation had to address two requirements: 1) the potential need to dry a given quantity of biomass and 2) the need to properly size the biomass for a given combustion or gasification system. No attempts were made to demonstrate the drying potential of the equipment purchased to support biomass storage and preparation capabilities.

The EERC's primary objective for fuel-sizing equipment was adequate capacity (227 to 454 kg/hr, or 500 to 1000 lb/hr) and size reduction capabilities to specifically match fuel size requirements for existing pilot-scale combustion and gasification systems. To address biomass fuel-sizing requirements, the EERC purchased a used hammer mill and a new platform feeder and conveyor to support operation of the hammer mill. The hammer mill is a rebuilt electrically driven Jacobson hammer mill, Model 556DF11, with a quick-change half-screen arrangement set up to discharge product through an outlet blower with product recovery in a cyclone. Processing kiln-dried hardwood scraps into wood chips resulted in a product rate of 227 kg/hr (500 lb/hr). Straw/grass-type biomass was also processed in the hammer mill, but the small quantity of material processed did not lend itself to determination of a product mass rate. Softwood and straw/grass-type biomass should result in a product rate of at least 454 kg/hr (1000 lb/hr).

A new platform feeder and conveyor were purchased to support operation of the hammer mill. Both the platform feeder and conveyor are electrically driven, and belt speed is adjustable. The platform feeder and conveyor have been operated for short periods of time to verify their general performance.

Flue Gas Instrumentation and Data Acquisition System Upgrades

The new flue gas sample conditioner and flue gas analyzers for O₂, CO, CO₂, SO₂, and NO_x were initially evaluated using nitrogen as a zero gas and certified calibration standards to verify performance within vendor-specified operating limits for accuracy and linearity. Output signals to the data acquisition system were also verified. Further verification of these instruments was completed as a function of shakedown tests with the modified pilot-scale combustion system. To date these instruments have met manufacturers' performance specifications as well as EERC expectations.

Upgrades to the data acquisition system software and hardware are an ongoing activity. These upgrades were not completed earlier in the project because they were considered a lower priority and were delayed pending completion of other project activities. Therefore, verification efforts associated with data acquisition system upgrades will be documented in the final project report to be submitted in June 2002.

Task 4 – Laboratory-Scale Testing and Fuel Characterization

Task 4 activities were initiated in February 2001 following the COR's approval of the revised Project Plan. A report documenting Task 4 experimental activities and results was prepared, and a draft report was submitted to the project COR on October 10, 2001. Following review and comment by the project COR, the Task 4 report was finalized in January 2002 and will be used in the preparation of a final project report. Results from the Task 4 effort are summarized in the following paragraphs.

Characterization of the biomass samples showed a much lower moisture content than the coal (7–12 wt% vs. 26 wt%) but twice as much volatile matter (69–77 wt% vs. 35 wt%). The fixed carbon for both the wood chips and the sunflower hulls was less than half of the Cordero Rojo coal (12–15 wt% vs. 34 wt%). The sunflower hulls had 1.5 times the inorganic content as the coal (7.3 wt% vs. 4.9 wt%), while the wood chips contained a very low percentage of inorganics at 0.63 wt%. This is almost an order of magnitude lower than the coal and the sunflower hulls. The hydrogen for the three fuels was similar (6–7 wt%), with the carbon content somewhat lower in the biomass fuels compared to the coal (44–47 wt% vs. 50 wt%). Nitrogen content in the sunflower hulls was similar to that of the coal (1 wt%). The wood nitrogen level, however, was a factor of 5 lower (0.2 wt%). Sulfur levels were 0.35 wt% in the coal, 0.27 wt% in the hulls, and 0.18 wt% in the wood. Chlorine levels in the biomass fuels were significantly higher at 588 and 649 ppm in the hulls and wood, respectively, while the coal only contained 57 ppm (all on an as-received basis). This high chlorine content could potentially be a corrosion problem and should be further investigated.

The inorganic distribution in the wood and coal is fairly similar, with the exception of the wood being enriched in alkali and alkaline-earth elements and the coal having a higher sulfur level, as previously stated. The sunflower hulls, on the other hand, contain significantly higher phosphorus and potassium than the coal, with almost 60 wt% potassium and 8 wt% phosphorus. The hulls have much less silica, alumina, and calcium compared to the coal and wood. Table 3 summarizes the routine analyses completed for the parent fuels and fuel blends in support of Task 4.

Table 3. Proximate and Ultimate Analysis of Fuels

	Cordero Rojo Coal	Sunflower Hulls Biomass	Wood Chips Biomass	80% Coal– 20% Sflr Hulls	60% Coal– 40% Sflr Hulls	80% Coal– 20% Wd Chips	60% Coal– 40% Wd Chips
Proximate Analysis, as-received, wt%							
Moisture	26.30	11.60	7.30	23.36	20.42	22.50	18.70
Volatile Matter	35.00	69.45	76.82	41.89	48.78	43.36	51.73
Fixed Carbon	33.76	11.61	15.25	29.33	24.90	30.06	26.36
Ash	4.94	7.34	0.63	5.42	5.90	4.08	3.22
Ultimate Analysis, as-received, wt%							
Hydrogen	6.19	6.71	6.12	6.29	6.40	6.18	6.16
Carbon	49.66	44.41	46.85	48.61	47.56	49.10	48.54
Nitrogen	1.08	1.01	0.17	1.07	1.05	0.90	0.72
Sulfur	0.35	0.27	0.18	0.33	0.32	0.32	0.28
Oxygen	37.78	40.25	46.05	38.27	38.77	39.43	41.09
Ash	4.94	7.34	0.63	5.42	5.90	4.08	3.22
Heat Content, Btu/lb	8862	7815	8274	8653	8443	8744	86267
Chlorine, ppm							
Dry Basis	77	665	700	195	312	202	326
As Received	57	588	649	149	248	156	265
XRF Analysis Oxide, wt% of Ash							
SiO ₂	30.0	4.8	28.4	22.0	16.0	30.0	29.8
Al ₂ O ₃	22.1	1.6	11.3	15.5	10.6	21.6	21.0
Fe ₂ O ₃	7.4	0.7	10.3	5.3	3.7	7.4	7.7
TiO ₂	1.9	0.1	0.5	1.3	0.9	1.9	1.7
P ₂ O ₅	1.2	8.0	1.4	3.4	5.0	1.2	1.2
CaO	29.9	12.8	29.2	24.4	20.3	29.8	29.8
MgO	5.5	9.9	6.1	6.9	7.9	5.6	5.5
Na ₂ O	1.7	0.0	5.0	1.1	0.8	1.9	2.1
K ₂ O	0.4	62.1	7.8	20.2	34.8	0.7	1.2

Entrained fly ash and deposits were obtained in the CEPS combustor for the parent coal and coal biomass blends of 80–20 coal–biomass and 60–40 coal–biomass. The deposits were collected on removable cooled probes for analysis and determination of growth rates and deposit strength.

The highest deposit growth rate was found for the parent coal fired without biomass. This deposit, however, had the lowest strength of any of the deposits generated. The highest-strength deposit was the 60–40 Cordero Rojo–sunflower hull blend, which also had the lowest growth rate. The PSD gives some clues as to growth and strength development. Previous work conducted at the EERC indicates that biomass fuels tend to have inorganic constituents that are significantly smaller than those of coals, and this is what is seen with these biomass fuels. However, these data are from CCSEM analysis which can only measure particle sizes larger than 1 μm and cannot account for anything smaller. Smaller fly ash particles tend to remain entrained in the gas stream and flow around the tubes following stream lines where larger-size particles will have enough mass to exit

the gas stream lines, resulting in deposition as a function of inertial impaction. Larger particles will also grow a deposit at a higher rate than the same number of small impacting particles. This size distribution can also help to partially explain the strength development as well. Smaller particles have a greater surface area than larger particles and, given the same viscosity or stickiness, will bind a deposit together better because of the larger amount of sticky surface available.

Overall, the 20% biomass blends do not appear to be a cause for concern with respect to ash deposition or corrosion. For the 40% biomass blends, higher chlorine content may create some longer term corrosion problems, especially when the biomass is cofired with low-sulfur coals. Ash deposition as a function of deposit strength did increase for the 40% sunflower hull blend and some caution may be required at this higher blend ratio.

As previously stated, the nitrogen content is similar for the coal and the sunflower hulls but much lower in the wood. However, this was not reflected in the flue gas NO_x concentrations measured during the laboratory-scale combustion tests. All of the biomass-coal blends resulted in higher NO_x concentrations than the parent coal. This is perplexing because it is generally found that the high concentration of volatiles found in biomass fuels as compared to coal have had the effect of reducing NO_x emissions when cofiring. Therefore, these NO_x concentration data are more likely a function of the laboratory-scale combustion system configuration and operating conditions (temperature, residence time, and excess air level) than fuel properties. The sulfur levels were much lower in the biomass fuels, and this was directly reflected in the flue gas SO_2 concentrations observed.

The CHF analysis is a series of selective chemical leachings that quantify organically bound inorganics and minerals that are less than 1 μm in size. Organically bound inorganics are found only in low-rank fuels and comprise the bulk of the inorganics that are less than 1 μm in size. Low-rank subbituminous and lignite coals act as ion-exchange materials, with alkali and alkaline earth elements such as Ca^{++} , Na^+ , and K^+ attaching to carboxylic acid groups in the coal. Up to half the calcium and all of the sodium and potassium present in the coal ash may be bound in this way. When the coal is burned, these highly dispersed elements have a high propensity to interact with other minerals present as well as form very fine ash. In the case of biomass fuels characterized in this study, it is believed that the majority of the inorganic material found to be leachable by water and ammonium acetate is in water-soluble form rather than organically associated as in coals. Generally, these materials will be more reactive than coal minerals because of a smaller size range but less reactive than organically associated materials.

The PCQUEST model predicts a higher propensity for high-temperature fouling and slagging with the sunflower hull blends and only a slightly higher propensity with the wood chip blends when compared to the coal. This is exactly what is seen in the experimentally derived deposit growth strength development. The tube erosion numbers are higher for the coal and are probably related to the greater content of larger silicate particles. The rest of the predictive values are relatively the same for all of the fuels.

Predicted deposition rates do not reflect what was seen in the laboratory-scale combustion and deposition tests. The deposition rate for the biomass blends is predicted to be higher than that of the

pure coal. This is exactly the opposite of what was seen in the deposition tests. This deposition rate formula was empirically derived for coal and obviously does not apply to coal–biomass blends.

Task 4 results and recommendations were used in the development of final test plans for the Task 5 pilot-scale combustion tests. Based on the results detailed in the Task 4 report, recommendations considered in the planning of pilot-scale grate-fired system shakedown tests and the two pilot-scale coal–biomass cofiring tests to be completed include the following:

- 1) Use Cordero Rojo subbituminous coal for shakedown tests documenting fouling and slagging characteristics as well as fine particulate concentrations and bulk flue gas composition (oxygen, carbon dioxide, carbon monoxide, sulfur dioxide, and nitrogen species).
- 2) For the two cofiring tests, use blend ratios of 40% biomass and 60% coal (40% sunflower hulls–60% Cordero Rojo coal and 40% wood residue–60% Cordero Rojo coal) to obtain data that would represent a worst-case scenario for practical biomass cofiring with respect to potential adverse ash impacts.
- 3) Cofiring tests should include fine particulate sizing analysis.
- 4) Special attention should be paid toward characterizing fine particulate to determine concentrations of potassium chlorides and sulfates and phosphates which may impact performance with respect to fouling and slagging as well as fine-particle emissions.

Task 5 – Pilot-Scale Testing and Reporting

Task 5 activities during this reporting period included preparation of project reports as well as the completion of two pilot-scale coal–biomass cofiring tests. Specific reporting requirements have included monthly Federal Assistance Program/Project Status Reports, quarterly updates of the Federal Assistance Milestone Plan and Milestone Log, and semiannual Technical Progress Reports. The pilot-scale testing component of this task began in January 2002 following the completion of Task 3. Task 5 pilot-scale tests were completed in February 2002, followed by sample analyses completed in March. Work on a draft final project report began in March, and the EERC expects to submit the draft report to the project COR for review in May 2002.

A draft test plan was prepared in December 2001 for the pilot-scale biomass-cofiring tests and submitted to the project COR for review. The draft test plan was approved by the project COR during a telephone conversation in mid-December and was subsequently finalized. A copy of the test plan is included as Appendix A. A baseline coal test (Cordero Rojo subbituminous coal) was completed in mid-January as part of Task 3 shakedown activities. The first pilot-scale coal–biomass grate-fired combustion test was completed in late January 2002. This test involved cofiring a blend ratio of 40 wt% biomass (wood chips) and 60 wt% coal (Cordero Rojo subbituminous). The same blend ratio was used in early February for the second coal–biomass combustion test, cofiring sunflower hulls and Cordero Rojo subbituminous coal. Data evaluation is ongoing, therefore, results

from these pilot-scale grate-fired tests are not available for inclusion in this report. Data from all three tests will be summarized and the results discussed in the final project report.

CONCLUSIONS AND RECOMMENDATIONS

The modified pilot-scale combustion system can successfully be used in a grate-fired or pc-fired configuration. Future projects should consider further modifications to the biomass feed system supporting grate firing, depending on the material type and feed rate. Biomass fuel particle size and process parameters should be carefully considered for each material type fired.

Biomass storage, handling, and processing capabilities at the EERC should be adequate to support future biomass pilot-scale combustion and gasification projects. Storage and handling capabilities may also effectively support small demonstration projects. The only exception would be bulk material drying beyond simply surface moisture.

Characterization of the biomass samples showed a lower moisture and sulfur content than the coal but twice as much volatile matter. The fixed carbon for both the wood chips and the sunflower hulls was less than half of the Cordero Rojo coal. The sunflower hulls had 1.5 times the ash content as the coal, while the wood chips contained a very low percentage of ash, nearly an order of magnitude lower. Chlorine levels in the biomass fuels were an order of magnitude higher than the coal.

The inorganic distribution in the wood and coal was fairly similar, with the exception of the wood being enriched in alkali and alkaline-earth elements and the coal having a somewhat higher sulfur level. The sunflower hulls, on the other hand, contain significantly higher phosphorus and potassium than the coal, with almost 60 wt% potassium and 8 wt% phosphorus. The hulls have much less silica, alumina, and calcium compared to the coal and wood.

The CHF analysis of the biomass fuels indicated that the majority of the inorganic material found to be leachable by water and ammonium acetate is in water-soluble form rather than organically associated as in coals. Generally, these materials will be more reactive than coal minerals because of a smaller size range but less reactive than organically associated materials. Therefore, when firing biomass, these highly dispersed elements have a high propensity to interact with other minerals present as well as form very fine ash.

During laboratory combustion tests, the highest deposit growth rate was found for the parent coal fired without biomass. This deposit, however, had the lowest strength of any of the deposits generated. The highest-strength deposit was the 60–40 Cordero Rojo–sunflower hull blend, which also had the lowest growth rate. These observations are believed to be a function of ash PSD as well as chemistry.

Although more volatile or aerosol flue gas components are generated with the biomass blends, such as chlorides and sulfates of potassium, these fine components seem to agglomerate and actually

show more coalescence in the fine <10 μm (<0.0004 in.) fraction compared to the baseline coal. Particulate control should not be an issue with these blends.

The PCQUEST model predicts a higher propensity for high-temperature fouling and slagging with the sunflower hull blends and only a slightly higher propensity with the wood chip blends when compared to the coal. This is exactly what is seen in the experimentally derived deposit growth strength development. The tube erosion numbers are higher for the coal and are probably related to the greater content of larger silicate particles. The rest of the predictive values are relatively the same for all of the fuels.

Predicted deposition rates do not reflect what was seen in the laboratory-scale combustion and deposition tests. The deposition rate for the biomass blends is predicted to be higher than that of the pure coal. This is exactly the opposite of what was seen in the deposition tests. This deposition rate formula was empirically derived for coal and obviously does not apply to coal–biomass blends.

Overall, the 20% biomass blends do not appear to be a cause for concern with respect to ash deposition or corrosion. For the 40% biomass blends, higher chlorine content may create some longer-term corrosion problems, especially when the biomass is cofired with low-sulfur coals. Ash deposition as a function of deposit strength did increase for the 40% sunflower hull blend and some caution may be required at this higher blend ratio.

Task 5 pilot-scale grate-fired combustion tests have been completed cofiring blend ratios of 40 wt% biomass (wood chips or sunflower hulls) and 60 wt% coal (Cordero Rojo subbituminous). However, analytical and data review activities are incomplete. Therefore, no conclusions can be drawn at this time.

REFERENCES

1. Mann, M.K.; Spath, P.L. The Net CO₂ Emissions and Energy Balances of Biomass and Coal-Fired Power Systems. In *Proceedings of the 4th Biomass Conference of the Americas: Biomass: A Growth Opportunity in Green Energy and Value-Added Products*; Overend, R.P.; Chornet, E., Eds.; 1999; Vol. 1, pp 379–385.
2. Bhattacharya, S.C. State of the Art of Biomass Combustion. *Energy Sources* **1998**, *20*, 113–135.
3. Easterly, J.L.; Burnham, M. Overview of Biomass and Waste Fuel Resources for Power Production. *Biomass Bioenergy* **1996**, *10* (2–3), 79–92.
4. Turnball, J.H. Strategies for Achieving a Sustainable, Clean and Cost-Effective Biomass Resource. *Biomass Bioenergy* **1996**, *10* (2–3), 93–100.
5. McGowin, C.R.; Wiltsee, G.A. Strategic Analysis of Biomass and Waste Fuels for Electric Power Generation. *Biomass Bioenergy* **1996**, *10* (2–3), 167–175.

6. Bauen, A.; Kaltschmitt, M. Contribution of Biomass Toward CO₂ Reduction in Europe. In *Proceedings of the 4th Biomass Conference of the Americas: Biomass: A Growth Opportunity in Green Energy and Value-Added Products*; Overend, R.P.; Chornet, E., Eds.; 1999; Vol. 1, pp 371–378.
7. Kwant, K.W.; van Leenders, C. Developments of Green Energy Market in the Netherlands and the Perspectives of Biomass. In *Proceedings of the 4th Biomass Conference of the Americas: Biomass: A Growth Opportunity in Green Energy and Value-Added Products*; Overend, R.P.; Chornet, E., Eds.; 1999; Vol. 1, p 1629.
8. Frandsen, F.J.; Nielsen, H.P.; Jensen, P.A.; Hansen, L.A.; Livbjerg, H.; Dam-Johansen, K.; Sorensen, H.S.; Larsen, O.H.; Sander, B.; Henriksen, N.; Simonsen, P. Deposition and Corrosion in Straw- and Coal–Straw Co-Fired Utility Boilers. In *Proceedings of the Engineering Foundation Conference on the Impact of Mineral Impurities in Solid Fuel Combustion*; Kona, HI, Nov 2–7, 1997; Wall, T.F.; Baxter, L.L., Eds.; 1997; 14 p.
9. Frandsen, F.J.; Nielsen, H.P.; Hansen, L.A.; Hansen, P.F.B.; Andersen, K.H.; Sorensen, H.S. Ash Chemistry Aspects of Straw and Coal-Straw Cofiring in Utility Boilers. In *Proceedings of the 15th Annual International Pittsburgh Coal Conference*; Sept 14–18, 1998; 14 p.
10. Skrifvar, B.; Lauren, T.; Backman, R.; Hupa, M. The Role of Alkali Sulfates and Chlorides in Post Cyclone Deposits from Circulating Fluidized Bed Boilers Firing Biomass and Coal. In *Proceedings of the Engineering Foundation Conference on the Impact of Mineral Impurities in Solid Fuel Combustion*; Kona, HI, Nov 2–7, 1997; Wall, T.F., Baxter, L.L., Eds.; 1997; 10 p.
11. Jensen, P.A.; Stenholm, J.; Hald, P. Deposition Investigation in Straw-Fired Boilers. *Energy Fuels* **1997**, *11*, 1048–1055.
12. Olanders, B.; Steenari, B. Characterization of Ashes from Wood and Straw. *Biomass Bioenergy* **1995**, *8* (2), 105–115.
13. Nordin, A. Chemical Elemental Characteristics of Biomass Fuels. *Biomass Bioenergy* **1995**, *8* (2), 339–347.
14. Boylan, D.M. Southern Company Tests of Wood/Coal Cofiring in Pulverized Coal Units. *Biomass Bioenergy* **1996**, *10* (2–3), 139–147.
15. Brouwer, J.; Owens, W.D.; Harding, S.; Heap, J.P. Cofiring Waste Biofuels and Coal for Emission Reduction. In *Proceedings of the 2nd Biomass Conference of the Americas: Energy, Environment, Agriculture, and Industry*; Portland, OR, Aug 21–24, 1995; NREL/CP-200-8098, DE95009230, 1995; pp 390–399.

16. Rudinger, H.; Kicherer, A.; Greul, U.; Spliethoff, H.; Hein, K.R.G. Investigations in Combined Combustion of Biomass and Coal in Power Plant Technology. *Energy Fuels* **1996**, *10*, 789–796.
17. Hughes, E.; Tillman, D. Biomass Cofiring: Status and Prospects 1996. In *Proceedings for the Engineering Foundation Conference, Biomass Usage for Utility and Industrial Power*; Snowbird, UT, April 28 – May 3, 1996; 19 p.
18. Battista, J.; Tillman, D.; Hughes, E. Cofiring Wood Waste with Coal in a Wall-Fired Boiler: Initiating a 3-Year Demonstration Program. In *Proceedings of BioEnergy 98: Expanding BioEnergy Partnerships*; Madison, WI, Oct 4–8, 1998; pp 243–250.
19. Moore, T. Harvesting the Benefits of Biomass. *EPRI Journal* **1996**, May/June, 16–25.
20. Prinzing, E.E.; Hunt, E.F. Impacts of Wood Cofiring on Coal Pulverization at the Shawville Generating Station. In *Proceedings for Engineering Foundation Conference: Biomass Usage for Utility and Industrial Power*; Snowbird, UT, April 28 – May 3, 1996; 15 p.
21. Gold, B.A.; Tillman, D.A. Wood Cofiring Evaluation at TVA Power Plants. *Biomass Bioenergy* **1996**, *10* (2–3), 71–78.
22. Miles, T.R.; Miles, T.R., Jr.; Baxter, L.L.; Bryers, R.W.; Jenkins, B.M.; Oden L.L. Boiler Deposits from Firing Biomass Fuels. *Biomass Bioenergy* **1996**, *10* (2–3), 125–138.
23. Moe, T.A. *Wastepaper Pellets as a Source of Fuel for Auxiliary Home Heating*; Final Report for Western Area Power Administration; Energy & Environmental Research Center: Grand Forks, ND, June 1995; 21 p.
24. Miles, T.R.; Miles, T.R., Jr.; Baxter L.L.; Bryers, R.W.; Jenkins, B.M.; Oden, L.L. Boiler Deposit from Firing Biomass Fuels. *Biomass Bioenergy* **1996**, *10* (2–3), 125–138.
25. Aerts, D.J.; Ragland, K.W. Cofiring Switchgrass in a 50-MW Pulverized Coal Utility. In *Proceedings of BioEnergy 98: Expanding BioEnergy Partnerships*; Madison, WI, Oct 4–8, 1998; pp 295–305.
26. Segrest, S.A.; Rockwood, D.L.; Stricker, J.A.; Green, A.E.S.; Smith, W.H.; Carter, D.R. Biomass Cofiring with Coal at Lakeland, Florida, Utilities. In *Proceedings of BioEnergy 98: Expanding BioEnergy Partnerships*; Madison, WI, Oct 4–8, 1998; pp 315–325.
27. Kendall, A. Barriers to the Progress of Bioenergy. *Energy World* **1996**, May, 10–13.
28. Graham, R.L.; Lichtenberg, E.; Roningen, V.O.; Shapouri, H.; Walsh, M.E. The Economics of Biomass Production in the United States. In *Proceedings of the 2nd Biomass Conference of the Americas: Energy, Environment, Agriculture, and Industry*; Portland, OR, Aug 21–24, 1995; NREL/CP-200-8098, DE95009230, 1995; pp 1314–1323.

29. Sondreal, E.A.; Benson, S.A.; Hurley, J.P.; Mann, M.D.; Pavlish, J.H.; Swanson, M.L.; Weber, G.F.; Zygarlicke, C.J. Review of Advances in Combustion Technology and Biomass Firing. *Fuel Process. Technol.* **2001**, *71* (1–3), 7–38.
30. D.R. Piperno. *Phytolith Analysis*; Academic Press: New York, 1988.
31. Baxter, L.L.; Miles, T.R.; Miles Jr., T.R.; Jenkins, B.M.; Milne, T.; Dayton, D.; Bryers, R.W.; Oden., L.O. The Behavior of Inorganic Material in Biomass-Fired Power Boilers: An Overview of the Alkali Deposits Project. In Bridgwater, A.V.; Boocock, D.G.B., Eds.; *Developments in Thermochemical Biomass Conversion*; Blackie Academic & Professional: London; 1997; Vol. II, pp 1424–1444; NICH Report No. 24259.
32. Robinson, A.; Baxter, L.; Junker, H.; Shaddix, C.; Freeman, M.; James, R.; Dayton, D. Fireside Issues Associated with Coal-Biomass Cofiring. Presented at BioEnergy '98, Madison, WI, Oct 4–8, 1998.
33. Kautz, K.M. Slagging, Fouling, and Corrosion on the New Generation of German Boilers Designed for the Combustion of a Broad Range of Bituminous Coal of Worldwide Origin. In *Proceedings of the Engineering Foundation Conference: Fouling of Heat Exchanger Surfaces*; Bryers, R.W. Ed.; United Engineering Trustees, Inc., 1983; pp 371–388.
34. Williams, R.B.; Jenkins, B.M.; Bakker, R.R.; Baxter, L.L. Investigation of Superheater Fouling in Biomass Boilers with Furnace Exit Gas Temperature Control. In *Proceedings of the 4th Biomass Conference of the Americas: Biomass: A Growth Opportunity in Green Energy and Value-Added Products*; Overend, R.P.; Chornet, E., Eds.; 1999; Vol. 2, pp 1393–1399.
35. Frandsen, F.J.; Nielsen, H.P.; Jensen, P.A.; Hansen, L.A.; Livbjerg, H.; Dam-Johansen, K.; Sorensen, H.S.; Larsen, O.H.; Sander, B.; Henriksen, N.; Simonsen, P. Deposition and Corrosion in Straw and Coal–Straw Co-Fired Utility Boilers. In *Proceedings of the Engineering Foundation Conference on the Impact of Mineral Impurities in Solid Fuel Combustion*; Kona, HI, Nov 2–7, 1997; Wall, T.F.; Baxter, L.L., Eds.; 1997; 14 p.
36. Nielsen-Philbert, H. Deposition and High-Temperature Corrosion in Biomass-Fired Boilers, Ph.D. Thesis, Technical University of Denmark, Department of Chemical Engineering, Nov 1998, 126 p.
37. Obernberger, I.; Dahl, J.; Brunner, T. Formation, Composition and Particle Size Distribution of Fly-Ashes from Biomass Combustion Plants. In *Proceedings of the 4th Biomass Conference of the Americas: Biomass: A Growth Opportunity in Green Energy and Value-Added Products*; Overend, R.P.; Chornet, E., Eds.; 1999; Vol. 2, pp 1377–1384.
38. Folkedahl, B.C.; Zygarlicke, C.J.; Hutton, P.N.; McCollor, D.P. Biomass for Energy–Characterization and Combustion Ash Behavior. In *Proceedings of Power Production in the 21st Century: Impacts of Fuel Quality and Operations*; Harding, N.S.; Baxter, L.L.; Wigley, F.; Frandsen, F., Eds.; Snowbird, UT, Oct 28 – Nov 2, 2001.

39. Folkedahl, B.C.; Zygarlicke, C.J.; Strege, J. Influence of Biomass Cofiring on PM_{2.5} Ash Produced in a 7-kW Coal Combustion System. Presented at the NETL PM_{2.5} Conference, Pittsburgh, PA, April 9–10, 2002, 2 p.
40. Zygarlicke, C.J.; Pavlish, J.H.; Laumb, J.D. Fuel and Combustion Characteristics of Rice Straw Lignin. To be presented at Bioenergy 2002: Bioenergy for the Environment, Boise, ID, Sept 22–26, 2002.
41. Zygarlicke, C.J.; McCollor, D.P.; Toman, D.L.; Dahl, J. Ash Interactions During the Cofiring of Biomass with Fossil Fuels. In *Proceedings of the 26th International Technical Conference of Coal Utilization, and & Fuel Systems*; Clearwater, FL, March 5–8, 2001; pp 237–248.
42. Zygarlicke, C.J.; Pavlish, J.H.; Laumb, J. Suitability of Rice Straw Lignin as Boiler Fuel. In *Proceedings of the 5th Biomass Conference of the Americas, Bioenergy and Biobased Products: Technologies, Markets, and Policies*; Orlando, FL, Sept 17–21, 2001; 2 p.
43. Zygarlicke, C.J.; Pavlish, J.H.; Gunderson, J.R.; McCollor, D.P. Ash Behavior and Combustion Performance During the Cofiring of Rice Straw Lignin and Coal. In *Proceedings of the 9th Biennial Bioenergy Conference: Moving Technology into the Marketplace*; Buffalo, NY, Oct 15–19, 2000; 2000; 12 p.
44. Zygarlicke, C.J.; Eylands, K.E.; McCollor, D.P.; Musich, M.A.; Toman, D.L. Impacts of Cofiring Biomass with Fossil Fuels. In *Proceedings of the 25th International Technical Conference on Coal Utilization and Fuel Systems*; Clearwater, FL, March 6–9, 2000; pp 115–126.
45. *Electricity from Biomass: National Biomass Power Program Five-Year Plan (FY 1994–FY 1998)*; Solar Thermal and Biomass Power Division, Office of Solar Energy Conversion, U.S. Department of Energy, U.S. Government Printing Office: Washington, DC, 1993; 43 p.
46. Mann, M.D. *Modular Fluid Bed Biocombustor – Phase 1 and 1A Final Report*; Final Report for Sandia National Laboratories Contract No. BC-0002C; Report No. 99-EERC-12-03; Energy & Environmental Research Center: Grand Forks, ND, 1999; 67 p.
47. Schmidt, D.D.; Pinapati, V.S. *Opportunities for Small Biomass Power Systems*; Final Technical Report for U.S. Department of Energy Contract No. DE-FG02-99EE35128; Report No. 2000-EERC-11-01; Energy & Environmental Research Center: Grand Forks, ND, Nov 2000.
48. Jenkins, B. University of California-Davis. Personal communication, Dec 2000.

49. Obernberger, I.; Dahl, J. University of Graz-Austria. Personal communication, Dec 2000.
50. Frandsen, F. Technical University of Denmark. Personal communication, May 2000.
51. Kiel, J. Energy Research Foundation of the Netherlands. Personal communication.
52. Reidl, R.; Dahl, J.; Obernberger, I.; Narodslawsky, M. Corrosion in Fire-Tube Boilers of Biomass Combustion Plants. In *Proceedings of the China International Corrosion Control Conference 1999*; Beijing, China, Oct 1999; China Chemical Anticorrosion Technology Association (CCATA) Paper No. 90129.
53. Benson, S. Microbeam Technologies Incorporated. Personal communication, Dec 2000.
54. Hinman, N. BCI International. Personal communication, Oct 2000.
55. Wood P.; McFadden, M. Ogden Power Pacific, Inc. Personal communication, June 1999.
56. Baxter, L. Brigham Young University. Personal communication, Dec 2000.
57. Schmidt, D.D.; Pavlish, J.H.; Plasynski, S. Biomass Cofiring: Low-Rank Coal and District Energy Cogeneration. *Cogeneration and On-Site Power Production* **2001**, 2 (6).
58. Hutton, P.N. *Cofiring of Biomass at the University of North Dakota*; Final Report for U.S. Department of Energy Cooperative Agreement No. DE-FC26-00NT40807; EERC Publication 2002-EERC-01-01; Energy & Environmental Research Center: Grand Forks, ND, Jan 2002.
59. Schmidt, D.D. *Cofiring of Biomass with Lignite Coal*; Final Report for U.S. Department of Energy Cooperative Agreement No. DE-FC26-00NT40900; EERC Publication 2002-EERC-01-03 Energy & Environmental Research Center: Grand Forks, ND, Jan 2002.

LIST OF ACRONYMS AND ABBREVIATIONS

Btu	British thermal unit
°C	degrees Celsius
CCSEM	computer-controlled scanning electron microscopy
CEPS	conversion and environmental process simulator
CHF	chemical fractionation
cm	centimeter
CO	carbon monoxide
CO ₂	carbon dioxide
COR	Contracting Officer's Representative
CTF	combustion test facility
DOE	U.S. Department of Energy
EERC	Energy & Environmental Research Center
EPA	U.S. Environmental Protection Agency
ESP	electrostatic precipitator
EU	European Union
°F	degrees Fahrenheit
FACT	Facility for the Analysis of Chemical Thermodynamics
FEGT	furnace exit gas temperature
Fe ₂ O ₃	iron(III) oxide
ft	foot
ft ²	foot, squared
ft ³	foot, cubed
GJ	gigajoule
hp	horsepower
hr	hour
in.	inch
kg	kilogram
kJ	kilojoule
km	kilometer
kV	kilovolt
kW	kilowatt
kWh	kilowatt-hour
lb	pound
m	meter
m ²	meter, squared
m ³	meter, cubed
MJ	megajoule
mm	millimeter
MMBtu	million (10 ⁶) British thermal unit
MSW	municipal solid waste
MW	megawatt
NETL	National Energy Technology Laboratory
NO _x	nitrogen oxides (nitric oxide and nitrogen oxide)

O ₂	oxygen
pc	pulverized coal
PCQUEST	Predictive Coal Quality Effects Screening Tool
ppm	parts per million
PSD	particle-size distribution
PURPA	Public Utility Regulatory Policy Act
RDF	refuse-derived fuel
RTI	Research Triangle Institute
scfh	standard cubic feet per hour
SiO ₂	silica (silicon dioxide)
μm	micron
UND	University of North Dakota
V	volt
W.C.	water column
wt%	weight percent

APPENDIX A

COMBUSTION TEST FACILITY EXPERIMENT OPERATING SPECIFICATION

COMBUSTION TEST FACILITY EXPERIMENT OPERATING SPECIFICATION

Pilot-Scale Grate-Fired System

Project Title: Barriers to the Utilization of Biomass

Project Sponsor: National Energy Technology Laboratory, U.S. Department of Energy

Combustion Test No.: AF-Stoker-01, January 17, 2002

AF-Stoker-02, January 28, 2002

AF-Stoker-03, February 7, 2002

EERC Fund No.: 4525

EERC DISTRIBUTION: G. Weber
J. Gunderson
C. Zygarlicke
B. Folkedahl
B. Riske
K. Uhrich
Instrument Shop

INTRODUCTION

The objective of these three test periods is to demonstrate the performance of the recently assembled pilot-scale grate-fired combustion simulator and determine the impact of cofiring biomass with coal on grate-fired system operability, ash deposition on convective pass simulation surfaces, and particulate mass loading and particle-size distribution at the inlet of an electrostatic precipitator (ESP). Cordero Rojo subbituminous coal will be used as the baseline fuel as well as in the coal-biomass blends. The biomass fuels will include clean wood chips and sunflower hulls. The biomass blend ratios will be 40 wt%. Standard 5.25-hr ash-fouling tests will be performed using the system's steam-cooled probes inserted into the duct at the furnace exit. U.S. Environmental Protection Agency (EPA) Method 5 sampling will be used to establish the dust loading mass entering the ESP and to collect a bulk ash sample for chemical and physical characterization by other biomass projects. In addition, a multicyclone sample will be collected at the ESP inlet during each test to determine the aerodynamic size distribution of the fly ash entering the ESP. Ash samples from each cyclone fraction as well as the backup filter will be made available to other biomass projects for characterization.

TESTING PROCEDURES AND PARAMETERS

Each test will involve a single day of operational activity using the combustion test facility (CTF) in a grate-fired configuration. The CTF grate-fired system will be preheated firing natural gas

through the preheat burner. The heat-up rate will be 200°F/hr (111°C/hr) or less during the 8-hr heat-up period. Table 1 shows the data sheets required and how frequently the data should be recorded during each test period.

Before initiating gas firing, preheat the ESP, initiate airflow through the grate, and start the cooling-water flows. When the furnace exit temperature has been stabilized at 1800°F (983°C), turn off the natural gas preheat burner and initiate solid fuel feed to the grate. Adjust the combustion airflow through the grate and overfire air ports as necessary to achieve desirable combustion conditions on the grate. Using adjustments to the fuel feed rate, establish and maintain a 1800°F (983°C) furnace exit temperature. Once the desired combustion conditions have been achieved on the grate and the furnace exit temperature stabilized at 1800°F (983°C), insert the convective pass probe bank into the furnace exit duct. Maintain steam cooled surface temperatures at 1000°F (538°C) for the 5.25-hr test duration.

The sampling cyclone will be used for periodic fly ash sampling. Make sure the heat tape is on and operating prior to beginning each test. Particulate control will be accomplished using the ESP. Set orifice differential pressure at 4 in. W.C. (7 mmHg). Initiate particulate sampling at the inlet to the ESP as soon as is practical to ensure completion within the 5.25-hr test duration.

The data sheets to be used during each test period are shown in Table A1. Data sheet entries will be made according to the table every hour. Data historians for the computer data acquisition system are to be turned on during heat-up and can be turned off after shutdown procedures are completed. Table A2 shows the general test parameters.

Shutdown procedures for each test will proceed as follows:

- After removal of the fouling probe bank following 5.25 hours of operation and completion of flue gas-sampling activities, excess fuel will be removed first from the biomass hopper and then from the coal hopper to a level of approximately 12 in. (30 cm) above the grate.
- Open fuel hopper nitrogen purges to 100 scfh (2.8 m³/hr).
- Close steam supply valve leaving control valves open to purge all steam from the lines.
- Open bottom ash hopper door and collect contents as the bottom ash sample.
- Continue fuel feed until no new fuel enters the active grate area.
- Increase overfire air to 60 scfm (1.7 m³/min). Turn off all air to the grate and replace with nitrogen.
- Adjust furnace pressure to -1 in. W.C. (-2 mmHg), adjusting overfire air as necessary.
- Turn off ram and reset to zero position. Turn off ram positioner air supply and remove ram from the grate.

Table A1. Data Sheets

Data Sheet 1 (2 pages)	System Pressures	Every hour
Data Sheet 2 (3 pages)	Air and flue gas temperatures	Every hour
Data Sheet 3	Water temperatures	Every hour
Data Sheet 4	Flue gas analyzers	Every hour
Data Sheet 5	Stoker parameters	Every hour

Table A2. Test Parameters

Parameter	Set Point
Fuel	<u>Stoker-01</u> Cordero Rojo coal, 73 lb/hr <u>Stoker-02</u> Cordero Rojo coal, 45 lb/hr Wood chips, 30 lb/hr (60/40 wt%) <u>Stoker-03</u> Cordero Rojo coal, 46 lb/hr Sunflower hulls, 31 lb/hr (60/40 wt%)
Furnace Exit Temperature Comb. Air Preheat Temp. Pri./Sec. Air Orifice Tertiary 1 and 2 Air Orifice Conv. Probe Bank Surface Temp. ESP Temp. ESP Voltage Orifice Diff. Press. Set Point Grate Airflows Zone 1 Front of Grate Zone 2 Middle Front Zone 3 Middle Back Zone 4 Back of Grate Overfire Airflow	1800°F +/- 10°F 500°F during start-up/turn preheat off during solid fuel firing 1.179-in. bore (grate airflows) 0.800-in. bore (overfire airflows) 1000°F 300° to 350°F Adjust to 60 kV or higher 4 in. W.C. 18 scfm, adjust as necessary 30 scfm, adjust as necessary 28 scfm, adjust as necessary 24 scfm, adjust as necessary 10 to 20 scfm, adjust as necessary
Oxygen Carbon Dioxide Carbon Monoxide Sulfur Dioxide Nitrogen Oxides Cooling Water Temp.	8 vol% @ 1.50 total A/F ratio Monitor/record <25 ppm Monitor/record Monitor/record 140°F maximum

- Use grate rake to push all fuel/ash remaining on grate surface into the bottom ash hopper at the discharge end of the grate.

- Turn off fans and nitrogen and allow system to cool.
- All water flow streams will remain on overnight as the system cools.

COAL, SLAG, AND ASH SAMPLING AND ANALYSIS REQUIREMENTS

- Particulate sampling during each test period will include an EPA Method 5 and a multicyclone at the inlet to the ESP. Retain samples, including filters, for characterization.
- Fuel samples will be collected for each solid fuel type fired. One composite fuel sample for each fuel type will be submitted for analyses following completion of each test period.
- Fly ash samples will be collected using the sampling cyclone during each test period. Submit samples to Jay Gunderson.
- Fouling deposits will be collected from the probes at the conclusion of each test, weighed, and submitted to Jay Gunderson.
- ESP fly ash will be collected and weighed at the conclusion of each test.
- Bottom ash will be collected and weighed at the conclusion of each test.
- Other ash material recovered from the system during maintenance will be collected for possible characterization.

Analyses required are shown in Table A3.

Table A3. Sample Analyses

Composite Fuel Samples: <ol style="list-style-type: none"> 1. Proximate 2. Sulfur 3. Carbon, Hydrogen, Nitrogen 4. Heating Value (Btu) 5. Chlorine 6. X-Ray Fluorescence Ash 7. CCSEM 8. Chemical Fractionation 	Fouling Deposits: <ol style="list-style-type: none"> 1. Point Count 2. Morphology 3. X-Ray Fluorescence 4. X-Ray Diffraction
Bottom Ash: <ol style="list-style-type: none"> 1. X-Ray Fluorescence 2. Carbon, Hydrogen, Nitrogen 	ESP Hopper Ash: <ol style="list-style-type: none"> 1. Carbon, Hydrogen, Nitrogen 2. Malvern Particle Size 3. X-Ray Fluorescence