

# **BARRIER ISSUES TO THE UTILIZATION OF BIOMASS**

## **Semiannual Technical Progress Report**

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## **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 for biomass fuels compared to the design fuel, vaporizing alkali and chlorides which then condense on rear walls and heat exchange tube banks in the convective pass of the stoker, 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 collected, analyzed, and reported 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 March 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 involves modification of an existing pilot-scale pulverized coal-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 ongoing with completion anticipated in November 2001.

Task 3, Verification Testing of the Simulator, will begin as soon as Task 2 is completed. The pilot-scale grate-fired simulator will undergo verification testing to ensure the modified system (fuel prep and feed, combustor, and flue gas analyzers) operates as intended and its relevance to full-scale systems. Fuels will be selected for verification testing based on the EERC's knowledge of full-scale grate-fired system performance. Data to be compared will include grate ash properties, fly ash properties, and flue gas properties. Minor adjustments will be made to the system as necessary. Completion of Task 3 is anticipated in November 2001.

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, Task 5 testing will be performed in the pilot-scale grate-fired system. Two separate biomass cofired tests are 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, wood chips and sunflower hulls, will be blended at a level determined from the laboratory-scale testing. The results for the pilot-scale grate-fired system will be analyzed and compared to existing data for pc-fired simulation and existing full-scale data. Completion of the Task 5 pilot-scale grate-fired combustion tests is anticipated in December 2001.

This semiannual technical progress report documents project activities and summarizes results for the period April through September 2001. The focus of the discussion concerns Task 2, Modification of Pilot-Scale Combustion System, and Task 4, Laboratory-Scale Testing and Fuel Characterization.

## **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 the design fuel, vaporizing alkali and chlorides which then condense on rear walls and heat exchange tube banks in the convective pass of the stoker, 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) is being modified to simulate a grate-fired system. However, the modifications planned will not prevent future 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 residence time of ash on the grate, time and temperature history of entrained ash, flue gas constituents, and conversion efficiency. The design strategy employed utilized a fixed-grate system with an air distribution plenum and a reciprocating ram to move ash and fuel across the grate. The system will utilize existing tertiary air piping to support operation of overfire air ports.

In addition to modifications directly to the CTF combustor, modifications were made to the fuel-feed system, and new preparation and handling equipment is being 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 will undergo verification testing to ensure the modified system (fuel prep and feed, combustor, and flue gas analyzers) operates as intended and its relevance to full-scale systems. Fuels will be selected for verification testing based on the EERC's knowledge of full-scale grate-fired system performance. Data to be compared will include grate ash properties, fly ash properties, and flue gas properties. Minor adjustments will be made to the system as necessary. If applicable, fuels for which existing data are available for the CTF's pc-fired configuration may be selected for comparison.

## ***Task 4 – Laboratory-Scale Testing and Fuel Characterization***

Fuel characterization and laboratory-scale combustion testing was 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.

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.,  $\text{SiO}_2$ ,  $\text{Fe}_2\text{O}_3$ , 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 compliment 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), testing will be performed in the pilot-scale grate-fired system. Two separate tests are 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 will be blended at a level determined from the laboratory-scale testing.

All of the results for the pilot-scale grate-fired system will be analyzed and compared to existing data for pc-fired simulation and existing full-scale data for grate-fired systems. 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 and will continue to be documented in monthly status reports and semiannual technical progress reports, with all of the project results to be compiled in a final project report. A draft final project report will be 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 Characterizations 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 and were 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. Design work related to the modification of the pilot-scale combustor began in January 2001 and was essentially completed in June 2001. The final design resulted in a rectangular grate (10" × 18" or 25 × 46 cm) with a surface area of 1.25 ft<sup>2</sup> (0.12 m<sup>2</sup>) in order to match the grate size to the combustion system firing rate (nominally 0.55 MMBtu/hr or 0.58 kJ/hr).

The fixed-grate arrangement will make use of a ram to periodically move fuel and ash across the grate. Ram actuation frequency and stroke length will depend on the fuel properties and firing rate. The fuel feed system will make use of a hopper/gate arrangement that will permit 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 will be 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.

Fabrication of the components for the grate-fired system began in June and are continuing. These components included the fixed grate, ram, and fuel feed hoppers; an ash collection area and access door for ash removal; and a refractory-lined carbon steel shell. Primary combustion air flow to the grate is controlled and divided into four zones over the length of the grate representing 20%, 25%, 25%, and 30% of the grate area, respectively. Overfire air will be injected through multiple opposing ports. The refractory-lined combustor will be preheated firing natural gas prior to initiating solid fuel firing. Two of the three refractory pours have been completed, and piping assembly for combustion air is in progress. The third and final refractory pour is expected to be completed in mid-October. Final assembly of the grate-fired combustion system will occur in November 2001.

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, with the last instrument delivered in July 2001. Assembly of the new flue gas sample conditioner and analyzers was completed in July. In general, the particular pieces of equipment ordered were selected because similar units previously acquired have proven to be very reliable and competitively priced. All of the analyzers are compact, permitting them to be mounted in a 19-in. rack. A single cabinet assembly was purchased to house the flue gas conditioner and analyzers, thus making the combination of components semiportable.

Biomass fuel prep and storage options at the EERC were reviewed. An existing rotary crusher and hammer mill can be used for some biomass fuels, and wood chippers are available locally on an as-needed basis. However, it was necessary to purchase a hammer mill for preparation of most biomass fuels. After reviewing options concerning new and used equipment, the EERC elected to

procure a rebuilt Jacobson hammer mill. Depending on the feed material type and size and desired product size, processing capacity should be 1000 to 2000 lb/hr (454 to 908 kg/hr). The rebuilt hammer mill was delivered in June, and performance processing wood and straw material was evaluated during a brief test in July 2001.

An order was placed with the hammer mill manufacturer for a blower assembly and additional screens. The blower assembly will permit the product from the hammer mill to be efficiently collected in a cyclone, with undersized material and dust collected in an existing dust control system. Final installation of the hammer mill will occur in October 2001 following delivery of the blower assembly.

A table feeder was procured to primarily deliver biomass to the hammer mill. However, the table feeder may have application for other biomass-handling requirements. The table feeder was ordered in June and delivered in August 2001. Assembly of the table feeder has been completed, and a short operational test has been successfully performed. Final installation of the table feeder will occur in conjunction with the hammer mill.

Existing storage bunkers at the EERC will not be appropriate for use with most biomass fuels because the bunkers were designed for coal. Therefore, alternative storage options were reviewed. The most flexible storage option identified was a “live bottom” or walking-floor-type trailer that could be tarped/covered. The EERC is in the process of procuring a used walking-floor semi-trailer from Research Triangle Institute (RTI) and obtaining other equipment for biomass fuel handling from the Environmental Protection Agency (EPA). Items of interest, being offered as surplus property by EPA, include conveyors, an hydraulically driven power unit, and other miscellaneous items. RTI and EPA personnel have indicated that release and delivery of the equipment items will not occur before late October 2001.

In addition to the walking-floor-type trailer, 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. The forage box was ordered in August and delivered in September 2001.

In order to properly site and facilitate the use of the forage box and walking-floor semi-trailer, the EERC submitted a request to DOE in September seeking permission to install a concrete pad (nominally 60 by 70 ft or 4200 ft<sup>2</sup> [18 by 21 m or 390m<sup>2</sup>]) at a nominal cost of \$15,000. The EERC anticipates receiving DOE approval in October 2001.

### ***Task 3 – Verification Testing of the Simulator***

No activity has occurred in the past 6 months. Task 3 is expected to begin in November with completion anticipated in early December 2001.

#### ***Task 4 – Laboratory-Scale Testing and Fuel Characterization***

Task 4 activities were initiated in February 2001. As of the preparation of this report, the EERC has completed experimental and analytical activities and has prepared and submitted to the project COR a draft report summarizing Task 4 activities and results.

Based on the results detailed in the Task 4 draft report, preliminary recommendations to be 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:

- 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).
- 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.
- Cofiring tests should include fine particulate sizing analysis.
- Special attention should be paid toward characterizing fine particulate to determine concentrations of potassium chlorides, 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 were limited to the preparation of project reports. Task 5 pilot-scale tests should be completed in December 2001, followed by sample analyses, with a draft final project report submitted to the project COR for review in February 2002.

## **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 using coal for power generation are considering the use of renewable fuels such as waste products or energy crop-derived biomass fuels as a potential economic 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 CO<sub>2</sub>-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 CO<sub>2</sub> 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 CO<sub>2</sub> 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 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 recent 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  $\text{NO}_x$ , destroys polychlorinated biphenyls, decreases smog, increases volatile organic compounds (greatly dependent upon combustion process), decreases  $\text{CO}$ , 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. 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 (29) 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 (30) along with issues related to the cofiring of biomass–coal blends (31).

The Energy & Environmental Research Center (EERC) is using this 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. 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 (32). 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 on superheater fouling (33). 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-Philbert et al. studied ash deposition mechanisms for grate-fired boilers that had been converted from coal to straw fuel (34, 35). 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 Zygarlicke et al. using simulated combustion testing to study the fundamentals of cofiring coal and wood, wheat straw, alfalfa stems, and rice straw lignin (36–38).

In summary, 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. This is the case for the feasibility study nearing completion for a small (<1-MW) stoker facility at the North Dakota State Penitentiary, which is considering not only the incorporation of a lower-cost biomass fuel but also a refurbishing of the stoker boiler to burn slightly hotter with the ability to generate more power and sell excess energy on the grid. These types of fuel and boiler changes can greatly affect ash behavior issues.

## **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 (39). 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 (39).

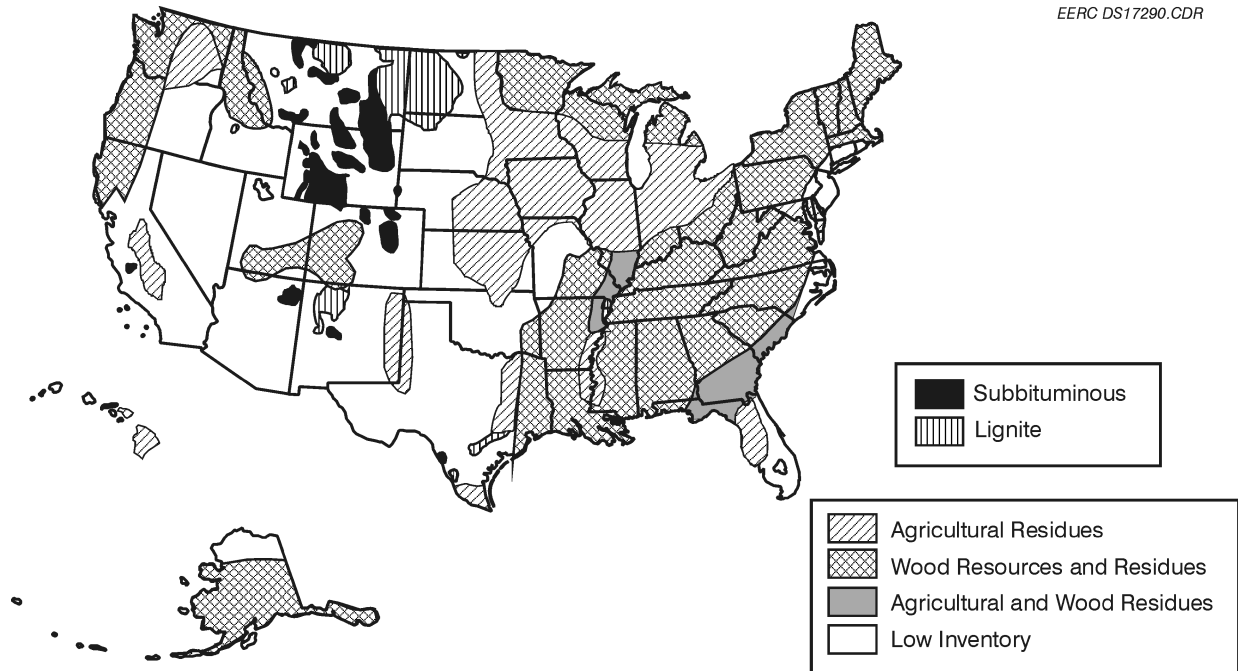


Figure 1. Location of agricultural and forest residues.

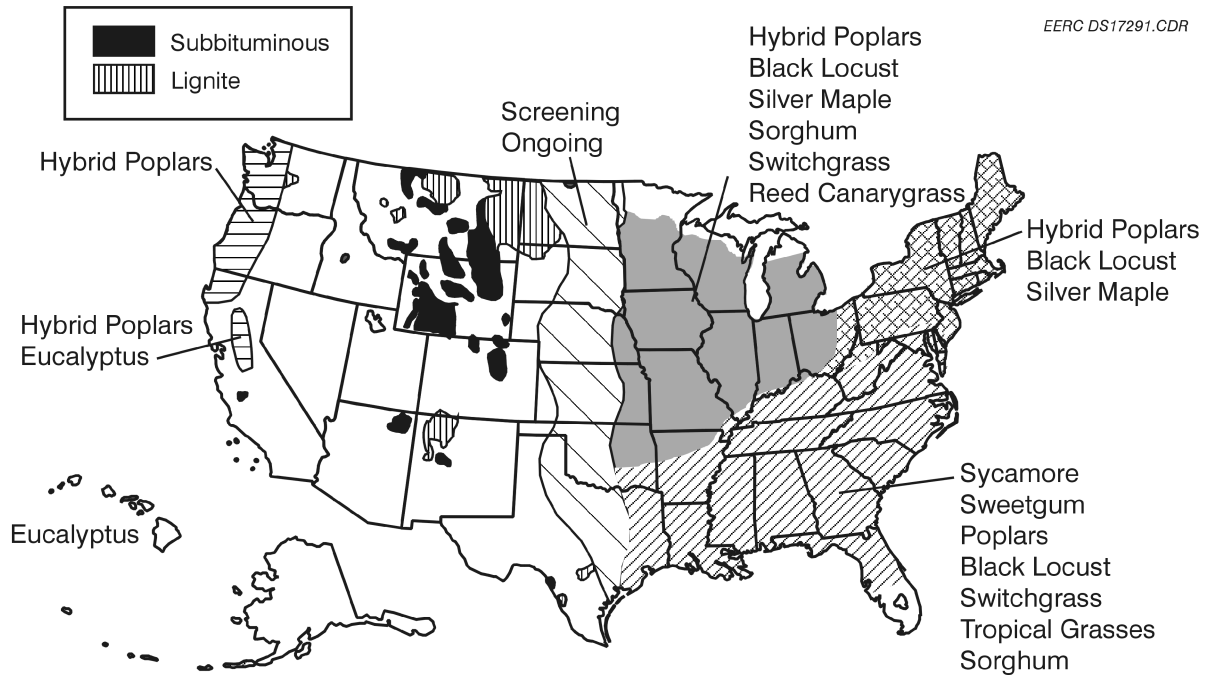


Figure 2. Promising locations for biomass energy crops.

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 (40):

- 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)

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) (41).

**Table 1. Biomass Subtypes**

<b>Agriculture Based</b>	<b>Forest Products</b>	<b>Urban Wastes</b>	<b>Dedicated Energy Crops</b>
<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, a substantial amount is still 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, trees are either 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. Nonwoody 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/m<sup>3</sup> (10–15 lb/ft<sup>3</sup>). 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/m<sup>3</sup> (25–27 lb/ft<sup>3</sup>). By comparison, the bulk density of coal is approximately 721 kg/m<sup>3</sup> (45 lb/ft<sup>3</sup>).

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/m<sup>3</sup> (1 to 2.5 lb/ft<sup>3</sup>), 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 these materials are used 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.

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 (42), Drs. Ingwald Obernberger and Jonas Dahl from the University of Graz-Austria (43), Dr. Fleming Frandsen from the Technical University of Denmark (44), and Dr. Jacob Kiel from the Energy Research Foundation of the Netherlands (ECN) (45) 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 cause 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 (46).

Discussions with Dr. Steve Benson from Microbeam Technologies Incorporated (47) 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 (48) and Paul Wood and Marty McFadden from Ogden Power Pacific, Inc. (49), 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 (50) 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  $\text{NO}_x$  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  $\text{CO}$ ,  $\text{O}_2$ , 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.

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.

### **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

**Table 2. Fuel Characteristics Requiring Special Attention**

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

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.

## **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 the U.S. Department of Energy (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 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. An existing EERC pilot-scale entrained combustion system is being modified to simulate grate-fired operation. However, the modifications planned will not prevent future operation of the pilot-scale combustion system in an entrained firing configuration. Design criteria for the modified system include 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 will require a modified approach to the conventional natural gas heatup for entrained system operation.

The EERC's combustion test facility (CTF), illustrated in Figure 3, is being 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 electrostatic precipitator or a pulse-jet fabric filter. The modifications to the system were designed to best simulate existing industrial systems. The design strategy employed utilized a fixed-grate system with an air distribution plenum and a reciprocating ram to move ash and fuel across the grate. The system will utilize existing tertiary air piping to support overfire air ports.

In addition to modifications directly to the CTF combustor, modifications were made to the fuel-feed system, and new preparation and handling equipment is being 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  $\text{NO}_x$ ,  $\text{SO}_2$ ,  $\text{O}_2$ ,  $\text{CO}$ , and  $\text{CO}_2$  analyzers as well as a new flue gas conditioning unit.

### Task 3 – Verification Testing of the Simulator

The pilot-scale grate-fired simulator will undergo verification testing to ensure the modified system (fuel prep and feed, combustor, and flue gas analyzers) operates as intended and its relevance to full-scale systems. Fuels will be selected for verification testing based on the EERC's knowledge

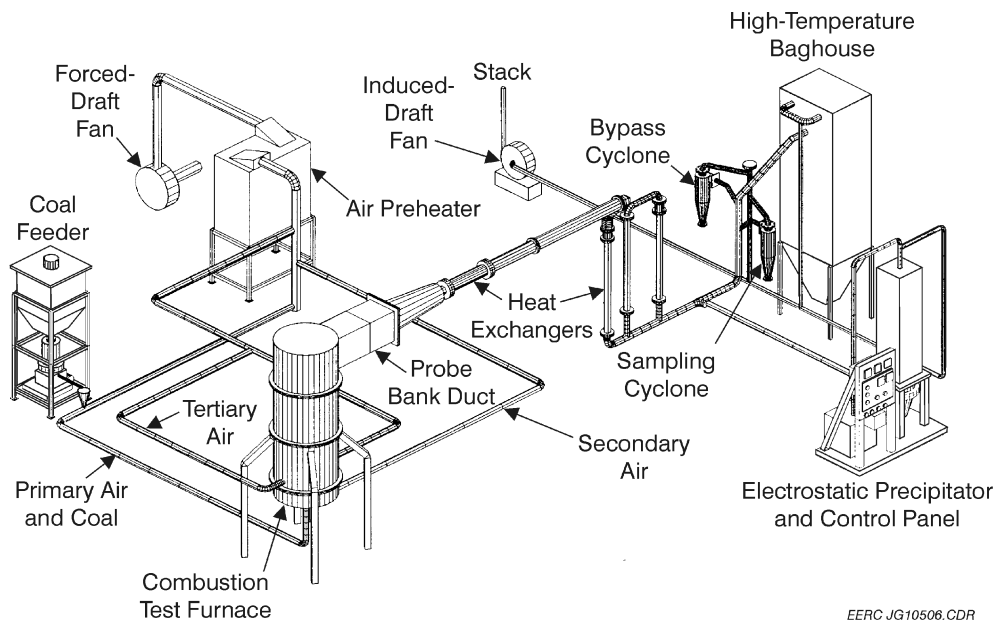


Figure 3. CTF and auxiliary systems.

of full-scale grate-fired system performance. Data to be compared will include grate ash properties, fly ash properties, and flue gas properties. Minor adjustments will be made to the system as necessary. If applicable, fuels for which existing data are available for the CTF's pc-fired configuration may be selected for comparison. It is assumed that a significant amount of the verification data will also be beneficial to 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. The EERC has had great success in using smaller systems such as the CEPS for initial screening studies.

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 was 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.,  $\text{SiO}_2$ ,  $\text{Fe}_2\text{O}_3$ , 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 compliment each other, together providing a reasonable prediction of relative fireside performance.

These combustion tests, along with the fuel, deposit, and fly ash analysis results, will provide 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 will be 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 only after testing is completed at the pilot scale.

### **Task 5 – Pilot-Scale Testing and Reporting**

Based on the results of the laboratory-scale work, testing will be performed in the pilot-scale grate-fired system. Two separate tests are 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 will be blended at a level determined from the laboratory-scale testing. A detailed test plan will be developed with input from DOE after the system design and laboratory-scale testing are complete.

All of the results for the pilot-scale grate-fired system will be analyzed and compared to existing data for pc-fired simulation and existing full-scale data. In addition to the technical assessment, an economic assessment will also be performed 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 and will continue to be documented in monthly status reports. This document is the semiannual technical progress report, with all of the project results to be compiled in a final project report. A draft final project report will be submitted to the DOE COR for review and comment prior to the final project report being issued. A final project review meeting may be held at the National Energy Technology Laboratory (NETL). Additionally, since biomass utilization is a rapidly growing topic, two conference trips are also planned to acquire the latest biomass knowledge and to convey any intermediate results to other researchers. Any papers prepared for these conferences will be submitted to the DOE COR for review and comment prior to their submission to the conference coordinator.

## **ACCOMPLISHMENTS**

Because of the limitations encountered with respect to the availability of EERC personnel in the past 6 months and the initial delay in final approval of the Project Plan, the EERC submitted a request in July 2001 to extend the project completion date through March 31, 2002. The DOE Contracting Officer notified the EERC of approval of the request in a letter dated August 20, 2001. Project activities in the past 6 months have been limited to Task 2, Task 4, and Task 5. The balance of this discussion will focus on accomplishments specific to project activities completed during the period April through September 2001.

### **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 Characterizations prior to authorizing the EERC to proceed with Task 4.

In response to the COR's request and several discussions in January 2001, the EERC prepared a revised Project Plan to address the COR's questions. The 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 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. However, because of limited personnel availability through September 2001, Task 2 activities have not progressed as originally planned, and completion of this task is not anticipated before late November 2001.

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 is expected to continue on an intermittent basis in support of fabrication activities as well as any 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, and fuel feed options relative to grate geometry and size. The final design resulted in a rectangular grate with a surface area of 1.25 ft<sup>2</sup> (10" × 18" or 25 × 46 cm) in order to match the grate size to the combustion system firing rate (nominally 0.55 MMBtu/hr or 0.58 kJ/hr).

The fixed-grate arrangement will require the use of a ram to periodically move fuel and ash across the grate. Ram actuation frequency and stroke length will depend on the fuel properties and firing rate. The fuel feed system will make use of a hopper/gate arrangement that will permit 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 will be 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, respectively. These activities were essentially completed in August 2001. Fabrication of the components for the grate-fired system began in June and are continuing. Figure 4 is an illustration of the grate-fired section to be 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 air flow to the grate is controlled and divided into four zones over the length of the grate representing 20%, 25%, 25%, and 30% of the grate area, respectively. Overfire air will be injected through multiple opposing ports not shown in Figure 4. The overfire air ports are located at an elevation comparable to the natural gas burner opening. The refractory-lined combustor will be preheated firing natural gas prior to initiating solid fuel firing.

Fabrication activities are continuing. Figure 5 is a photograph of the new grate-fired system components installed on the CTF. Two of the three refractory pours have been completed, and piping assembly for combustion air is in progress. The third and final refractory pour is expected to be completed in mid-October. Final assembly of the grate-fired combustion system will be delayed until November as a result of several pulverized fuel-fired biomass tests planned for the combustion system in late October and early November.

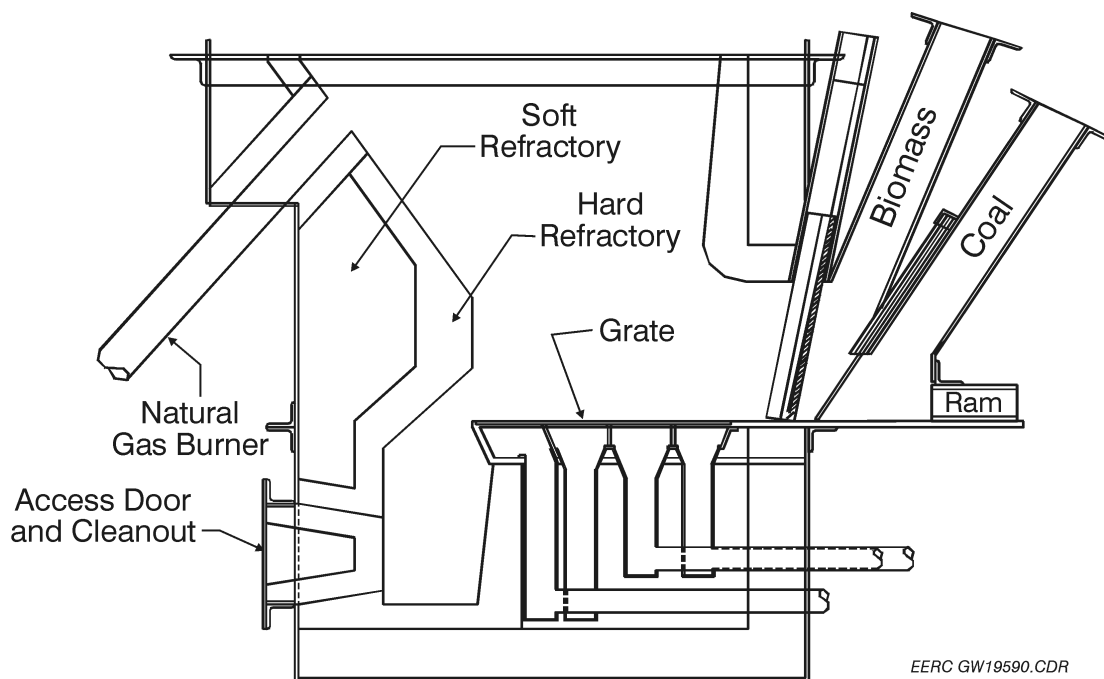


Figure 4. Illustration of components for the grate-fired system.



Figure 5. Photograph of grate-fired system components installed on CTF.

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, with the last instrument delivered in July. The flue gas sample conditioner selected was supplied by Baldwin Environmental, Inc. (Cooler Model 20410S and Conditioner Model 9BC3). This unit utilizes an electronic moisture condenser and a dual-stream conditioner, permitting simultaneous support of two sets of gas analyzers.

A single analyzer was selected for the measurement of oxygen, carbon dioxide, and carbon monoxide. Rosemount Analytical (Model NGA2000-MLT3 A, Multi-Method/Multi-Channel Analyzer with Internal Power Supply) supplied the analyzer. Oxygen measurement will be accomplished using a paramagnetic method with a minimum range of 0 to 5% and a maximum range of 0 to 100% on a dry volume basis. Carbon dioxide measurement will be accomplished using a nondispersive infrared absorption spectrophotometer method with a minimum range of 0 to 5% and a maximum range of 0 to 100% on a dry volume basis. Carbon monoxide measurement will be accomplished using a nondispersive infrared absorption spectrophotometer method with a minimum range of 0 to 100 ppm and a maximum range of 0 to 5000 ppm on a dry volume basis.

AMETEK Process & Analytical Instruments supplied the analyzer (Model No. 921, Nondispersive Ultraviolet Absorption Spectrophotometer) selected for the measurement of sulfur dioxide. Sulfur dioxide measurement will be accomplished using a nondispersive ultraviolet absorption spectrophotometer method with a minimum range of 0 to 500 ppm and a maximum range of 0 to 5000 ppm on a dry volume basis.

Rosemount Analytical supplied the analyzer (Model NGA2000-CLD, Chemiluminescence NO/NO<sub>x</sub> Analyzer) selected for the measurement of nitrogen species. NO/NO<sub>x</sub> measurement will be accomplished using a chemiluminescence method with a minimum range of 0 to 50 ppm and a maximum range of 0 to 1000 ppm on dry volume basis.

In general, the particular pieces of equipment ordered were selected because similar units previously acquired have proven to be very reliable and competitively priced. All of the analyzers are compact, permitting them to be mounted in a 19-in. rack. A single cabinet assembly was purchased to house the flue gas conditioner and analyzers, thus making the combination of components semiportable. Assembly of the new flue gas sample conditioner and analyzers was completed in July. In addition, output signals from the gas analyzers were incorporated into the data acquisition system. Therefore, the flue gas sample system is ready for use.

Biomass fuel prep and storage options at the EERC were reviewed. An existing rotary crusher and hammer mill can be used for some biomass fuels, and wood chippers are available locally on an as-needed basis. However, it was necessary to purchase a hammer mill for preparation of most biomass fuels. After reviewing options concerning new and used equipment, the EERC elected to procure a rebuilt Jacobson hammer mill. Depending on the feed material type and size and desired product size, processing capacity should be 1000 to 2000 lb/hr (454 to 908 kg/hr). The rebuilt hammer mill, shown in the Figure 6 photograph, was delivered in June and procurement of electrical support equipment was completed in July 2001. Hammer mill performance processing wood and straw material was evaluated during a brief test in July.

An order was placed with the hammer mill manufacturer for a blower assembly and additional screens. The blower assembly will permit the product from the hammer mill to be efficiently

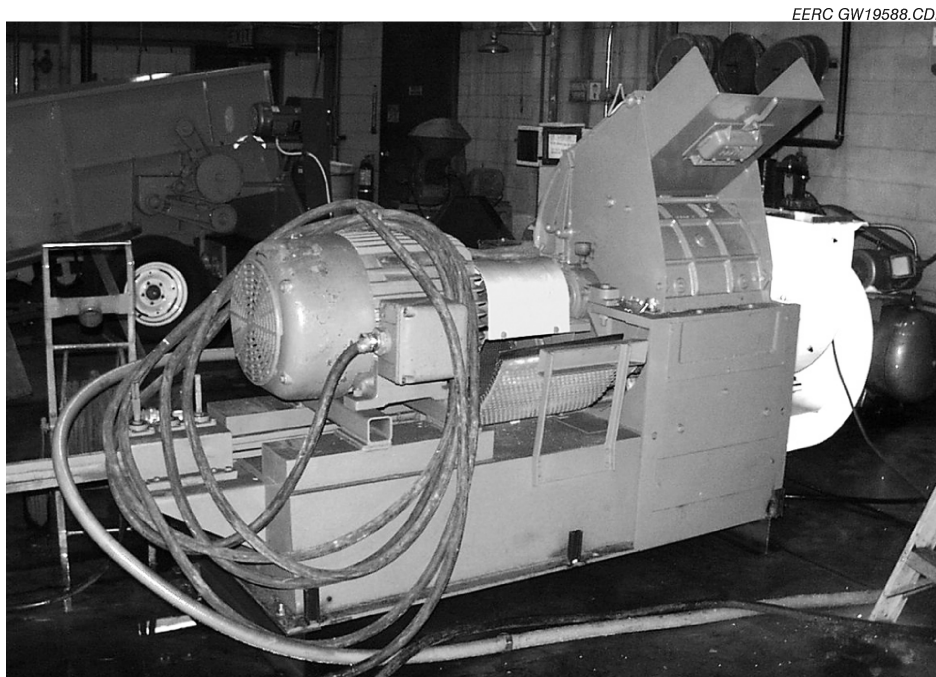


Figure 6. Photograph of rebuilt hammer mill.

collected in a cyclone, with undersized material and dust collected in an existing dust control system. Two screens, one with larger openings to produce a product better suited for grate-fired system applications, were ordered. Final installation of the hammer mill will be delayed until October based on notification received from the hammer mill manufacturer that forged parts for the blower assembly did not meet specifications and would have to be replaced by the manufacturer. Delivery of these parts is now anticipated in mid-October 2001.

A table feeder was procured to primarily deliver biomass to the hammer mill. However, the table feeder may have application for other biomass-handling requirements. The table feeder was ordered in June, delivered in August 2001, and is shown in the Figure 7 photograph. Assembly of the table feeder has been completed, and a short operational test has been successfully performed. Final electrical connections and location of the table feeder will be completed in October with the final installation of the hammer mill.

Existing storage bunkers at the EERC will not be appropriate for use with most biomass fuels because the bunkers were designed for coal. Therefore, alternative storage options were reviewed. The most flexible storage option identified was a “live bottom” or walking-floor-type trailer that could be tarped/covered. This type of unit could be used for biomass transport as well as storage. A tarped/covered unit would permit biomass storage for several months, if necessary, without weather impacts. The EERC is in the process of procuring a used walking-floor semitrailer and other equipment for biomass fuel handling and storage. EERC personnel found a used walking-floor semitrailer being offered by the Research Triangle Institute (RTI). The trailer had been used in support of an Environmental Protection Agency (EPA) biomass demonstration project. Other items related to the project were being offered by EPA as surplus property. Items of interest included



Figure 7. Photograph of table feeder.

conveyors, an hydraulically driven power unit, and other miscellaneous items. After speaking with RTI and EPA representatives, the EERC initiated procurement actions in order to obtain the equipment identified. However, RTI and EPA personnel have indicated that release and delivery of the equipment items will not occur before late October 2001.

In addition to the walking floor-type trailer, 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. The forage box was ordered in August, delivered in September 2001, and is shown in the Figure 8 photograph. Now that the forage box has arrived, a drive system will be assembled for the forage box using an electric motor and hydraulic pump.

In order to properly site and facilitate the use of the forage box and walking-floor semitrailer, the EERC submitted a request to DOE in September seeking permission to install a concrete pad (nominally 60 by 70 ft or 4200 ft<sup>2</sup> [18 by 21 m or 390 m<sup>2</sup>]). In addition, the concrete pad would 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 the used hammer mill and walking-floor semitrailer, the existing equipment budget will be adequate to cover the cost, nominally \$15,000, of installing the concrete pad.

### **Task 3 – Verification Testing of the Simulator**

No activity has occurred in the past 6 months. Task 3 is expected to begin in November, with completion anticipated in early December 2001.



Figure 8. Photograph of forage box.

## **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. As of the preparation of this report, the EERC has completed Task 4 experimental activities and has prepared a draft report summarizing Task 4 activities and results. The draft report was submitted to the project COR on October 10, 2001. Following review and comment by the project COR, the Task 4 report will be finalized, and results and recommendations will be used in the development of final test plans for the Task 5 pilot-scale combustion tests. A copy of the draft report is attached as Appendix A.

Based on the results detailed in the Task 4 draft report, preliminary recommendations to be 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, 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 were limited to the preparation of project reports. 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 will begin following the completion of Task 3. Task 5 pilot-scale tests should be completed in December 2001, followed by sample analyses, with a draft final project report submitted to the project COR for review in February 2002.

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