Results of Pilot-Scale Biomass Co-Firing for P.C. Combustors

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Summary

FETC's pilot-scale 500,000 Btu/hr Combustion and Environmental Research Facility (CERF) is investigating biomass co-firing issues in pulverized coal (pc) units. Technical issues include biomass fuel handling/processing, and biomass impacts on flame stability, combustibility, ash deposition, and emissions. This research has shown synergies, both positive and negative, where certain co-firing results are different from what is expected from coal and biomass alone.

This project is funded from FETC's Coal Utilization Science Advanced Research and Technology Development (AR&TD) Program to acquire basic combustion data, to both interpret and model results with the broad goal of assisting utility biomass co-firing demonstrations. FETC has a heavily industry-cost shared Cooperative Agreement with the Electric Power Research Institute (EPRI) for biomass co-firing demonstrations at seven U.S. utilities.

Biomass fuels include locally available waste materials, such as sawdust and wood chips from lumber mills, agricultural and forest residues, utility right-of-way residues, pallets, and nonrecyclable paper. Biomass also includes energy crops, such as fast growing grasses and short rotation woody trees that could be harvested specifically as a dedicated boiler fuel.

Introduction

Principal driving forces for governmental action to encourage biomass include the broad-based efforts to foster renewable energy and reduce fossil energy emissions of CO_2 as well as SO_2 and NO_x. Biomass combustion is seen as a means of closing the carbon cycle, as in effect, solar energy (photosynthesis) is converted to thermal energy.

A typical bituminous coal emits nearly 3 tons of CO_2 for each ton of coal burned, and on an energy basis this amounts to about 220 lb per MMBtu. For this reason, efforts at aimed at increased energy efficiency, both at the electric generation source (i.e., heat rate improvements at power plants) and end user (i.e., conservation) are central to any economic strategy aimed at reducing CO_2 in absolute terms.

While biomass combustion also produces CO_2 (e.g., wood is about 220 lb/MMBtu) at about the same level as coal on an energy equivalent basis, biomass CO_2 is often presented as effectively CO_2 neutral (i.e., no net CO_2) relative to fossil fuel combustion. Those encouraging biomass have framed the CO_2 issue as a fossil CO_2 issue, wherein the boundaries have been effectively defined around the coal fields. Of course, taking this argument to an extreme, where some might argue that the CO_2 in the atmosphere and that in biomass are exchangeable, leads to difficulties with respect to deforestation. Thus, the concept of sustainable energy and need for high thermal efficiency are key considerations for biomass power.

Of course, for biomass to be truly CO2 neutral from the standpoint of powerplant emissions to the atmosphere, an equivalent level of new biomass growth is needed to offset biomass combustion. Other issues that complicate the role of biomass power in terms of global climate change include the external energy required for growing (e.g., fertilizers), harvesting, and processing the biomass before its utilization in the power plants, as well as variable decomposition effects which release other greenhouse gases (e.g., methane). In short, the CO_2 and other greenhouse gases as well as feedback effects (e.g., induced changes in H_2O vapor, temperature) are classic problems of mass and energy balances, in terms of defining problem boundaries, identifying streams (inlet, outlet, accumulations), and time frame to understand and evaluate options/impacts for global climate change.

Notwithstanding the technical complexity and controversy surrounding these issues, there is clear evidence towards increasing renewable energy and biomass power capacity in the U.S. and abroad. This evidence may be found in some existing and proposed state and federal legislation, and the increasing worldwide interest in establishing climate change treaties in which greenhouse gas emissions would be curbed.

Some utilities currently use (or are considering) biomass wastes to reduce costs and/or be a good neighbor to large industrial customers or the community. Because the U.S. has considerable acreage of erodible soils that are being phased out of a federal subsidy program to prevent usage, certain states are examining energy crops, such as switchgrass, as a potential option for generating revenue. Several federal and state agencies (e.g., forest, fish and wildlife services) are interested in the improved habitat for birds that results from the tall switchgrass.

Many groups, including DOE's Energy and Efficiency (EE) Programs (which also sponsor DOE's Regional Biomass Energy Programs) have been studying waste resource assessments, developing energy crops, and focusing on biomass energy utilization issues. These utilization issues concern combustion in existing power plant designs, as well as developing dedicated biomass gasification and combustion systems for power generation. Traditionally, biomass-only boilers have not been very efficient, primarily due to high moisture and fuel handling, as well as high alkali contents that force lower steam temperatures. In addition, biomass-only plants tend to be much smaller in MW_e output than pc boilers which also impacts net boiler efficiencies, because it isn't practical to put in an elaborate turbine (e.g., multiple with reheat) systems with high capital costs in a small boiler. In addition, smaller boilers also have greater proportional parasitic power requirements.

Most of the known biomass co-firing experience has been in coal-fired cyclone and stoker boilers, where long residence times allow combustion of coarse particles. Stoker boilers include a grate over the bottom ash pit, to burn 1-inch by 1/4-inch coal, while cyclone and fluidized-bed boilers feed coal that is generally in the 1/8-inch by zero range. In contrast, comparatively little biomass co-firing has been performed in pulverized coal utility boilers, which represent the dominant form of U.S. power generation.

Biomass co-firing within the existing infrastructure of pc utility boilers is viewed as a practical means of encouraging renewable energy while minimizing capital cost requirements and maintaining the high efficiencies of pc boilers. The wide dispersion of pc boilers (in number and capacity) translates into significant potential opportunities for biomass utilization, even at levels of only 5-15% of the thermal input. While biomass co-firing in pc boilers appears promising, it does have risks, including some that are not obvious. This project seeks to identify methods and criteria to help determine which types of interactions might occur in a specific application.

Test Program

A major portion of the FETC biomass co-firing test program is being jointly conducted with researchers at Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL). While FETC can investigate larger size biomass particles and conduct long term tests to examine slagging/fouling and emissions during co-firing, SNL and NREL can acquire more fundamental data (e.g., relating to kinetics) and perform 100% biomass comparison tests to help discern synergies between coal and biomass combustion.

In general, SNL and NREL have focused on small particles with a minus 1-mm topsize. SNL is utilizing its 100,000 Btu/hr Multi-Fuel Combustor, which is equipped with laser diagnostics, while NREL is performing bench-scale studies using its gas chromatograph/molecular beam spectrometer with a small fixed-bed reactor. Together, the joint FETC/SNL/NREL effort will allow for a more comprehensive understanding of biomass co-firing impacts, particularly when coupled with the data from the utility co-firing demonstrations being pursued under an industry cost-shared Cooperative Agreement between FETC and the Electric Power Research Institute (EPRI).

The joint FETC/SNL/NREL test matrix includes three U.S. coals - Pittsburgh and Eastern Kentucky bituminous and Wyoming Powder River Basin subbituminous - with five biomass fuels, including switchgrass, hybrid willow, alfalfa stems, wood chips/sawdust, and nonrecyclable paper. The switchgrass, hybrid willow, and sawdust were obtained from utility co-firing demonstrations at the Madison Gas & Electric Blount Station, New York State Electric & Gas Greenidge Station, and General Public Utilities/Pennsylvania Electric Seward Station.

In addition to the joint FETC/SNL/NREL test matrix, other coals and biomass fuels are to be co-fired to allow for a broader effort. For example, at FETC biomass co-firing tests have been performed using a Montana subbituminous coal and an Iowa switchgrass, while other tests involve processed furniture wood waste (from plywood, particle board) which contains a nitrogen content about three times that of coal on an energy basis. At SNL, biomass co-firing tests have been conducted using American and Danish wheat straw in order to explore high alkali and chlorine contents.

Collectively, these coals and biomass fuels cover a wide range of key characteristics, such as moisture, heating value, coal composition (e.g., volatile matter, ash, sulfur, and nitrogen content), ash composition (e.g., alkali, calcium, iron) and ash fusion temperature profiles. The focus of the FETC/SNL/NREL work is to complete a Phase I study by October, 1998 that provides a broad-based understanding of coal and biomass synergistic effects in combustion.

Because biomass fuel handling - size reduction, injection technique - is perhaps the single most important technical issue in biomass co-firing in pc combustors, the FETC program objectives includes heavy emphasis in this area, including co-pulverization of coal and biomass in separate injection systems. Prior utility experiences have shown that biomass co-firing levels have often been limited to about 3-5% (mass basis) of the coal feed due to limitations (e.g., power consumption) in the existing pulverizers. Because many utility pc boilers are capacity limited by the existing pulverizers, separate injection systems for biomass offer the opportunity for slight increases in capacity. In addition, separate injection systems would be required to enable advanced concepts, such as biomass reburning, to be evaluated. Favorable biomass attributes for reburning include the low density and nitrogen contents of many biomass fuels.

For these reason, FETC is interested in evaluations of various types of solid mills, grinders, and pulverizers for the potential application of processing biomass fuels. Most of this work involves Cooperative Research and Development Agreements (CRADAs) with companies that have developed prototype mills. Under such CRADAs, these firms seek combustion/emissions data from CERF tests that would assist in defining mill parameters as it relates to achieving various size particle distributions. Such data would be valuable as these firms seek to scale-up their mills and partner with utilities on future biomass co-firing demonstration projects.

Combustion and Environmental Research Facility (CERF)

Commissioned in 1989, the 500,000 Btu/hr CERF was designed to achieve similarity with full-scale utility boilers, in terms of replicating typical specification ranges for burner relative mass flow, radiant furnace temperature distributions, gas residence time, and convective section gas velocity. Figure 1 presents an overall schematic of the CERF.

Although pilot-scale combustors cannot exactly duplicate conditions in utility boilers because of inherent distortions, such as heat release rates and surface-to-volume ratios, they have proven to be useful in examining the integrated effects of a number of interdependent design/operating variables. For example, fuel quality is assessed by comparing its pilot-scale performance with that of reference fuels for which full-scale performance is known.

The CERF is equipped to evaluate the following fuel characteristics: (1) transport, handling and storage, (2) combustibility, including flame stability and carbon conversion efficiency, (3) ash deposition rates, heat transfer properties (e.g., emissivity and thermal conductivity), and deposit removal characteristics (e.g., soot-blowing requirements), and (4) flue gas emissions, such as SO_2, NO_x, CO, total hydrocarbons, and particulates.

To-date, over twenty coals have been evaluated in terms of combustibility, slagging and fouling, and emissions. This includes run-of-mine, washed, and deep-cleaned coals, and various coal blends. The flexible design of the CERF has also facilitated the development and testing of various systems and concepts for improving combustion and reducing pollution. Completed projects include evaluation of: (1) in-furnace low-NO_x combustion concepts for gas and coal firing; (2) post-combustion flue gas cleanup technologies to reduce SO_2 and NO_x; (3) advanced diagnostic instrumentation for combustion processes; and (4) high-temperature ceramic and advanced alloys for heat transfer processes. Typically, the CERF research involves work with outside parties that bring ideas, hardware, or fuels for evaluation.

In this project, several technical issues are under investigation in conjunction with the joint studies being conducted at SNL and NREL, as well as the various utility co-firing demonstrations being performed under the FETC/EPRI Cooperative Agreement. These issues are summarized in Table 1.

Table 1. Technical Issues with Biomass Co-Firing

Defining the Fuel Handling Requirements for Successful Biomass Co-Firing
- How Big? Fuel Processing/Size Reduction Equipment
- How Wet? Moisture Content
- Where? Injection Location
- How Much? Percent of Total Thermal Input

Determine Impacts on NO_x Emissions
- Can biomass significantly lower NO_x, and if so, how?
- Trade offs with unburned carbon
- Can burner operation be altered to better accommodate biomass?

Ash Deposition (Slagging and Fouling) Behavior on Tube Surfaces
- Can volatile alkali from biomass become a flux for coal ash?
- Conditions where biomass ash and coal ash behave as separate particles

Impacts on Bottom and Fly Ash Characteristics
- Relevance to commercial ash utilization applications

This work is aimed at determining where synergies exist between biomass and coal combustion, and evaluating co-firing limits where significant benefits or problems might exist.

Biomass Analyses

Table 2 summarizes the ASTM proximate and ultimate analyses of various biomass fuels. These analyses were performed on air-dried biomass samples. Included are various biomass wastes, such as processed furniture waste sawdust, conventional lumber mill sawdust, and ground pallets, as well as energy crops, such as switchgrass and hybrid willow. Biomass fuels were obtained from sources located in Pennsylvania (PA), New York (NY), Wisconsin (WI), and Iowa (IA). Collectively, these biomass fuels are the subject of co-firing demonstrations that have been conducted or under consideration for future projects.

Air-drying was needed in order to blend biomass fuels with pulverized coal for a series of co-firing combustion tests. Because biomass is typically stored outside, actual moisture contents can be very high as a result of humidity, temperature, and other conditions (e.g., rain, snow). For example, actual as-received moisture contents for lumber mill sawdusts have been as high as 48-58 wt% while processed furniture waste sawdust samples of 18 wt% moisture have been observed. Consequently, comparing biomass samples on an air-dried basis is an informative means of comparing the intrinsic nature of the fuels, without the complications of variable weather, especially in terms of a proximate analysis.

Of note are the very low sulfur contents of biomass fuels. These levels are effectively so low that special low-sulfur (<0.1 wt%) standards, beyond standards that are normally used for coal analyses, are really needed to make very accurate determinations. Most biomass fuels are very low in chlorine content, and at the range (<0.04 wt%) of detectability limits.

Table 2. Biomass Fuel Analyses, Air-Dried

	Furniture Waste Sawdust (NY)	Lumber Mill Sawdust (PA)	Switch Grass (WI)	Hybrid Willow (NY)	Ground Pallets (PA)
Proximate, wt% (as received)					
Moisture	7.88	5.39	8.77	7.83	4.57
Volatile Matter	75.51	73.55	71.68	75.34	73.58
Fixed Carbon	15.53	19.59	11.19	11.04	6.74
Ash	1.08	1.47	6.95	5.80	15.11
Ultimate, dry wt%					
Hydrogen	7.09	6.26	6.02	6.02	4.80
Carbon	49.08	48.47	46.21	48.29	42.40
Sulfur	0.08	0.16	0.11	0.05	0.10
Nitrogen	3.25	0.59	0.94	1.20	0.22
Oxygen	39.16	42.93	37.56	38.15	36.65
Chlorine	0.17	<0.04	<0.04	<0.04	<0.04
Ash	1.17	1.56	9.16	6.29	15.83
Btu/lb, as-received	7764	7825	7037	7077	6737
Btu/lb, dry	8429	8271	7714	7628	7060
lb Ash/MMBtu	1.39	1.89	11.87	8.25	22.42
lb SO_2/MMBtu	0.19	0.39	0.29	0.13	0.28
lb NO_2/MMBtu	12.67	2.34	4.00	5.17	1.02

From Table 2, the biomass fuels cover a wide range of ash and nitrogen contents. Particularly noteworthy is the processed furniture waste sawdust, which has a very high nitrogen content (about 3 times that of coals on an energy basis) owing to the presence of various glues associated with the processed wood, such as particle board and plywood. Ground pallets have a high ash content, while the ash content of the energy crops (switchgrass and hybrid willow) is moderate relative to the sawdust fuels.

Table 3 presents the observed variability in biomass fuels, including those determined under an as-received basis, where moisture contents can vary considerably. In general, biomass fuels exhibit greater variability than typical coals in terms of ash, moisture, and nitrogen contents. In this respect, it is recommended that biomass fuels be thoroughly mixed to lessen variability during a series of combustion tests, especially when multiple test facilities and laboratories are involved.

Table 3. Variability of Biomass Fuel Analyses, Including As-Received

	Furniture Waste Sawdust	Lumber Mill Sawdust	Switchgrass
Moisture, wt% as-received	5.95 - 17.64	7.53 - 58.00	5.81 - 11.05
Ash, wt% dry	0.59 - 1.37	0.57 - 2.40	5.22 - 18.45
Sulfur, wt% dry	0.05 - 0.10	0.02 - 0.07	0.04 - 0.18
Nitrogen, wt% dry	2.32 - 4.32	0.12 - 0.72	0.59 - 1.20
Btu/lb, as-received	6966 - 7956	4872 - 7675	6400 - 7300

Of importance is that most biomass fuels can be air-dried to achieve moisture contents in the 7-8 wt% range. While this may not be practical for utility co-firing demonstrations, reduction (or maintenance) in surface moisture is important when comparing combustion results in different test facilities.

Table 4 summarizes the ASTM ash fusion profiles (under both reducing and oxidizing atmospheres) as well as ash composition results under the standard ashing at 750 °C. Variability data is also provided in terms of two different samples of processed furniture waste sawdust as well as two different sources of switchgrass (Iowa and Wisconsin) and sawdust (both from Pennsylvania).

In general, the biomass fuels have low ash fusion temperature characteristics, although (curiously) one lumber mill sawdust sample exhibited ash high fusion temperatures. Variability in ash composition results is also evident, and again points to the need to have well mixed biomass batches prior to small-scale combustion tests.

Collectively, these biomass fuels cover a wide range of characteristics that are important in terms of possible effects on ash deposition in terms of slagging and fouling. This can be clearly seen when considering important factors such as the acid/base ratio, silica/alumina ratio, iron and calcium contents, as well as the strong presence of alkali (sodium and potassium). In contrast to coals where sodium predominates, biomass alkali tends to be predominately potassium-based, which is partly attributable to the role potassium plays (e.g., fertilizers) in biomass production.

Table 4. Biomass Ash Fusion Characteristics

	Furniture Waste Sawdust (NY)		Lumber Mill Sawdust (PA)		Switch Grass		Hybrid Willow	Ground Pallet
	I	II	A	B	IA	WI	(NY)	
Ash Fusion, F (reducing)								
Initial	2310	2150	2130	2690	2090	2040	2070	nd
Softening	2340	2180	2150	2700	2240	2130	2110	nd
Hemispherical	2350	2220	2160	2710	2260	2220	2120	nd
Fluid	2360	2250	2170	2720	2350	2310	2200	nd
Ash Fusion, F (oxidizing)								
Initial	2420	2190	2140	2730	2240	2070	2120	nd
Softening	2440	2210	2160	2750	2290	2250	2150	nd
Hemispherical	2450	2220	2180	2760	2390	2320	2160	nd
Fluid	2460	2290	2190	2770	2520	2360	2240	nd
Ash Composition, wt%								
SiO_2	15.00	18.25	52.37	40.99	67.21	61.03	56.39	14.73
Al_2O_3	3.67	3.89	8.09	12.32	2.57	2.04	7.16	4.15
Fe_2O_3	22.06	10.28	9.89	7.32	3.86	7.21	5.90	10.49
TiO_2	5.31	7.46	0.48	0.63	0.15	0.22	0.90	8.78
CaO	29.51	22.81	12.31	15.75	11.85	9.50	16.26	37.37
MgO	4.40	3.43	1.13	1.76	4.33	4.89	2.62	6.27
Na_2O	13.58	7.45	0.34	0.78	0.34	0.81	1.99	11.68
K_2O	3.84	6.66	7.53	10.11	3.73	8.28	4.08	3.17
P_2O_5	0.00	3.02	0.71	0.87	2.09	3.99	1.99	0.00
lb alkali/MMBtu	0.27	0.10	0.14	0.07	0.37	1.08	0.50	3.30

From Table 4, biomass alkali content varies considerably among these fuels, covering a range of 0.07 to 3.30 lb/MMBtu. In general, biomass alkali has been reported to be potentially significant in terms of ash deposition when levels exceed 0.3 lb/MMBtu. Consequently, this entire biomass fuel matrix will enable considerable study of the potential synergies in ash deposition between biomass and coal during combustion.

Of importance in biomass combustion is the form of alkali, as this relates to alkali vaporization, mobility, and subsequent reactions during combustion. Towards this end, ash composition analyses will be conducted using lower ashing temperatures (e.g., 600 ^{o}C) as well as chemical ashing techniques in order to better characterize the biomass alkali in a manner consistent with other research groups.

CERF Biomass Co-Firing, Testing To-Date

The CERF testing to-date has successfully focused on two methods of co-firing. First, co-injection of pre-blended pulverized coal and biomass in the primary air; and second, separate injection of the biomass in the center of the CERF burner within an annulus of pulverized coal/primary air. Future tests in 1988 will examine advanced injection concepts, such as biomass reburning to reduce NO_x emissions.

At this juncture, some combinations of coals and biomass fuels have been studied over a range of 5-10% (energy basis) biomass co-firing levels. These tests have typically been of short duration, typically involving only 1-12 hours each, to become familiar with the various aspects of biomass co-firing in terms of CERF operations as well as impacts on combustion, ash deposition, and emissions measurements.

These early tests have contributed to a number of adjustments in the overall CERF biomass co-firing program. While this work is ongoing and still considered preliminary in terms of the conclusions, the following material is offered to illustrate the data analyses being performed.

CERF Biomass Co-Firing, Preliminary Combustion & Emissions Results

An important consideration has been examination of biomass particle size. Table 5 presents the variability in particle size distribution for an as-received conventional lumber mill sawdust. In actuality, four different sources of conventional lumber mill sawdusts have been examined with respect to particle size. Because of the various saw operations (e.g., circular versus band saws), wood feedstocks and products, sawdust can vary considerably in both size and shape. Consequently, sawdusts have been found which have been both coarser and finer than that presented in Table 5. In general, this variability increases with biomass topsize. Owing to their fibrous nature, which tends to result in sliver-shaped and other irregularly shaped particle, it can be very difficult to characterize the particle size of biomass fuels based on a singular smallest dimension.

Table 5. Particle Size Distribution for one Lumber Mill Sawdust

Mesh Size	wt% Retained, Range
+ 8 mesh	5.9 - 12.7
+ 20 mesh	49.6 - 66.9
+ 50 mesh	24.6 - 35.0
+ 100 mesh	1.6 - 5.6
Minus 100 mesh	1.0 - 2.3

In terms of FETC combustion tests, a key consideration has been to examine this size variability, along with moisture contents within each size fraction, as it relates to particle size and combustion effects. In addition, it is desired to determine maximum biomass sizes for complete burnout in suspension relative to pulverized coal. For this reason, a number of biomass fuels and processing techniques (screening, grinding) have been used in conjunction with the various biomass fuels.

The CERF co-firing tests have shown that plus 20-mesh biomass particles are too large to completely burn in the CERF's radiant section, which represents a total gas residence time of about 3 seconds. These larger biomass particles exhibit delayed combustion past the primary pulverized coal flame, resulting in still-burning particles/sparklers entering the CERF's convective section and bottom ash hopper.

The effects of large biomass particles on delayed combustion is clearly illustrated in Table 6, which summarizes the loss-on-ignition (LOI) for the bottom ash when co-firing biomass fuels with significant differences in size distribution. Typically, modest (5 wt% range) increases in flyash LOI were observed as a result of this delayed combustion, but such comparisons are much more dramatic when comparing bottom ash LOI, as it should be noted that bottom ash represents about 20% of the total ash.

Table 6. Biomass Particle Size Distributions and Bottom Ash Loss-on-Ignition for Two Biomass Fuels in CERF Co-Firing Tests

	Lumber Mill Sawdust	Processed Furniture Waste Sawdust
Mesh Size	*wt% Passing Through*	
8 mesh	97.1	100.0
20 mesh	24.6	98.6
50 mesh	4.1	54.8
100 mesh	1.6	18.1
200 mesh	0.7	5.0
CERF Co-Firing Test	*Bottom Ash LOI, wt%*	
5% TTI with Eastern Kentucky	52.0	0.8
10% TTI with Eastern Kentucky	74.9	0.7
10% TTI with Pittsburgh	50.0	4.1

The lumbermill sawdust was relatively coarse, with only 25% passing 20 mesh, and resulted in extremely high levels of bottom ash LOI in the 50-70 wt% range when co-firing with Pittsburgh and Eastern Kentucky coals. In contrast, the processed furniture waste sawdust, which was much finer with nearly 99% passing 20 mesh, resulted in much lower levels (0.7-4 wt%) of bottom ash

LOI.

Clearly, the co-firing of processed furniture waste sawdust bottom ash LOI was much closer to the normal parent coal operation where bottom ash LOI is essentially zero. These results suggest that plus-20 mesh particles are largely responsible for the increased LOI in the bottom ash.

The occurrence of delayed combustion with such particles (i.e., plus 20 mesh) is due to several factors. First, the intrinsic relationship between the size of biomass particles and their gross reactivity, in terms of the necessary residence time to complete combustion, especially for the biomass char. In addition, the available residence time is shortened for large particles owing to the greater proportional influence of gravity versus the burning pulverized coal/char which occurs in suspension within the bulk gas stream.

These results are consistent with the visual appearance of the still-burning, sparklers which were observed to be moving faster than the bulk gas (3-4 ft/sec) in the CERF's radiant combustor. Obviously, taking an extreme case, where particles would fall at the rate of gravity (accelerating at 32 ft/sec^2), the residence time for a 9 foot drop (i.e., the height of the CERF radiant furnace) would obviously be only a fraction of the total available 3 second gas residence time. Consequently, the plus 20-mesh particles appear to be travelling at some intermediate velocity which is greater than the bulk gas.

Because the CERF height is much less than a utility boiler, a question will exist in terms of correlating the CERF results (in terms of the combustion behavior of larger particles) with that observed in utility biomass co-firing demonstrations. This information will be needed to gauge the practical limits of biomass size distributions, as the CERF observations (e.g., increases in bottom ash LOI, presence of still-burning sparklers entering the convective section) will be expected to be more pronounced for a given fuel as compared to co-firing in a utility boiler. In this regard, some fundamental combustion modelling that results in improved benchmarking (i.e., utilizing the available data from bench-scale, pilot-scale, utility) would be very helpful.

In terms of gauging the significant impact of elevated bottom ash LOI, several points should be made. Because most (75-80%) of the total ash reports as fly ash, the influence of elevated bottom ash LOI on the overall fuel combustion efficiency is greatly lessened for a given fly ash LOI. However, elevated bottom ash LOI can be crucial in eliminating the marketability of the bottom ash. In addition, the presence of still-burning particles could negatively impact ash handing equipment in terms of potential for fires, etc. Obviously, still-burning particles that end up in the bottom ash will also result in still-burning particles being entrained in the high-velocity convective pass, where again the potential for fires and poor collection efficiencies in the downstream particulate removal (i.e., baghouse, electrostatic precipatators) would be of considerable concern. In addition, this behavior would also alter the heat absorption profiles in the boiler and convective pass, leading to reduced efficiency from considerations such as increased attemperation.

These CERF results suggest that plus-20 mesh particles lead to increased LOI in bottom ash
Clearly, defining a biomass size by a singular dimension does not adequately represent the potential for delayed combustion. Biomass particles are indeed multi-dimensional and irregular.

Owing to their fibrous nature, the biomass particles can often be sliver shaped, with a length that is many times that of the shortest dimension. Thus, while the shortest dimension may define its size distribution and behavior through the classifier, long sliver-shaped particles may pass through and still contribute to delayed combustion.

Recent CERF co-firing tests at 15% (energy basis) with highly processed switchgrass and hybrid willow (essentially 100% minus 1-mm) showed a significant reduction in delayed combustion, as sparklers were not observed entering the convective ash and bottom ash. At this topsize, long slivers (>1/4-inch) were not present. These results are consistent with preliminary SNL results, where biomass particles above 1 mm (16 mesh) have been observed to lead to elevated levels of unburned carbon.

The preliminary CERF test results have shown that the presence of biomass does not significantly impacting combustion (in terms of unburned carbon) of coal particles over the conditions studied to-date. Insignificant changes in flame root position and flame stability have been observed with low levels (<10%, energy basis) of biomass co-firing. The flame root position is determined as the distance from the burner exit where a thermocouple (placed through the center of the burner in the gas pilot) measures 1800 ^{oF}. For bituminous coals like Pittsburgh and Eastern Kentucky, the flame root position is typically 2.5-4.0 inches, depending upon burner conditions, such as secondary air swirl number and primary/secondary air ratio. For subbituminous coals, such as Wyoming Powder River Basin, the flame root position is greater, and in the 6-8 inch range.

When co-firing biomass at less than 10% of the thermal input, the flame root position has not changed significantly, and is generally within 1.5 inches of the baseline coal. When co-firing 15% 1-mm biomass (switchgrass and hybrid willow) in the form of pre-blended coal/biomass, some flame instabilities have occurred. While the flame root position has not increased dramatically, flame ignition was observed to be delayed, creating difficulties with the CERF's dual fire-eye flame detection system. These instabilities are believed to be related to instabilities in the CERF's indirect fired coal feeding system. Of note is that the 15% energy basis blend, amounts to about 1 lb of biomass per 3 lb of coal, and thus the blend takes on more of the biomass characteristics, in terms of forming loose and compressible clumps, and tends to feed with surging flow. Because the flame root position did not appreciably increase for these 15% co-firing tests, it is believed that such flame instabilities could be rectified with better feeder control and/or with separate biomass injection at the burner which would be more realistic in terms of utility applications at high co-firing levels. Future CERF tests will confirm this, and characterize 15% (blend) co-firing behavior with the Wyoming Powder River Basin coal.

In general and as expected, NO_x emissions have been reduced on a lb/MMBtu basis when co-firing biomass in the form of coal/biomass blends. Typically, this NO_x reduction has been less than what would be expected based on the baseline coal NO_x and the nitrogen content of the biomass. Typical baseline NO_x levels are 0.55-0.70 lb/MMBtu for the Pittsburgh and Eastern Kentucky coals, and about 0.50 lb/MMBtu for the Wyoming PRB coal. In a few instances, an increase in flame root position as a result of biomass co-firing as accompanied increased NO_x levels. Future tests will clarify the NO_x issue, especially with higher levels of co-firing, where greater differences in NO_x would be expected.

A few tests with separate injection of biomass at the CERF burner have been conducted. In these tests, biomass was fed by gravity down the center of the burner (former location of coal/primary air) while coal/primary air was rerouted to the annulus (former location of main natural gas) surrounding the biomass injection. With this scheme, baseline coal NO_x levels were quite high, and near 1 lb/MMBtu, as the coal/primary air underwent more rapid mixing with the secondary air. In these few biomass co-firing tests, a trend with respect to NO_x was not clear, perhaps owing to the dramatic change in coal/air mixing as a result of this configuration, as shown in Table 7. Future CERF tests will explore other configurations for separate biomass injection at the burner.

Table 7. Preliminary NO_x Results with Separate Biomass Injection

	NO_x ppm	NO_x lb/MMBtu
Baseline Pittsburgh Coal	818	1.1
5% TTI Lumber Mill Sawdust	952	1.3
5% TTI Processed Furniture Waste Sawdust	895	1.2
7% TTI Lumber Mill Sawdust	728	1.0
10% TTI Processed Furniture Waste Sawdust	937	1.3

Note: NO_x ppm is corrected to 3% O_2, dry basis

Future Work

A major initiative within the joint FETC/SNL/NREL test matrix are biomass co-firing tests where the same particle size so that the test facilities can be directly benchmarked against one another. This entails the processing of a large quantity (over 1000 lb) of biomass to a minus 1- mm topsize.

Future studies will examine the particle size issue, and complete a Phase I matrix consisting of three baseline coals and six biomass fuels. This matrix will include some FETC/SNL/NREL benchmarking tests using identically sized biomass fuels that will be co-fired at 15% on an energy basis. These benchmarking tests will enable direct comparison of FETC/SNL/NREL results with respect to combustion, ash deposition, and emissions and the formulation of a better understanding between coal and biomass synergies in combustion. Completion of this joint FETC/SNL/NREL Phase I project is scheduled for October, 1998.

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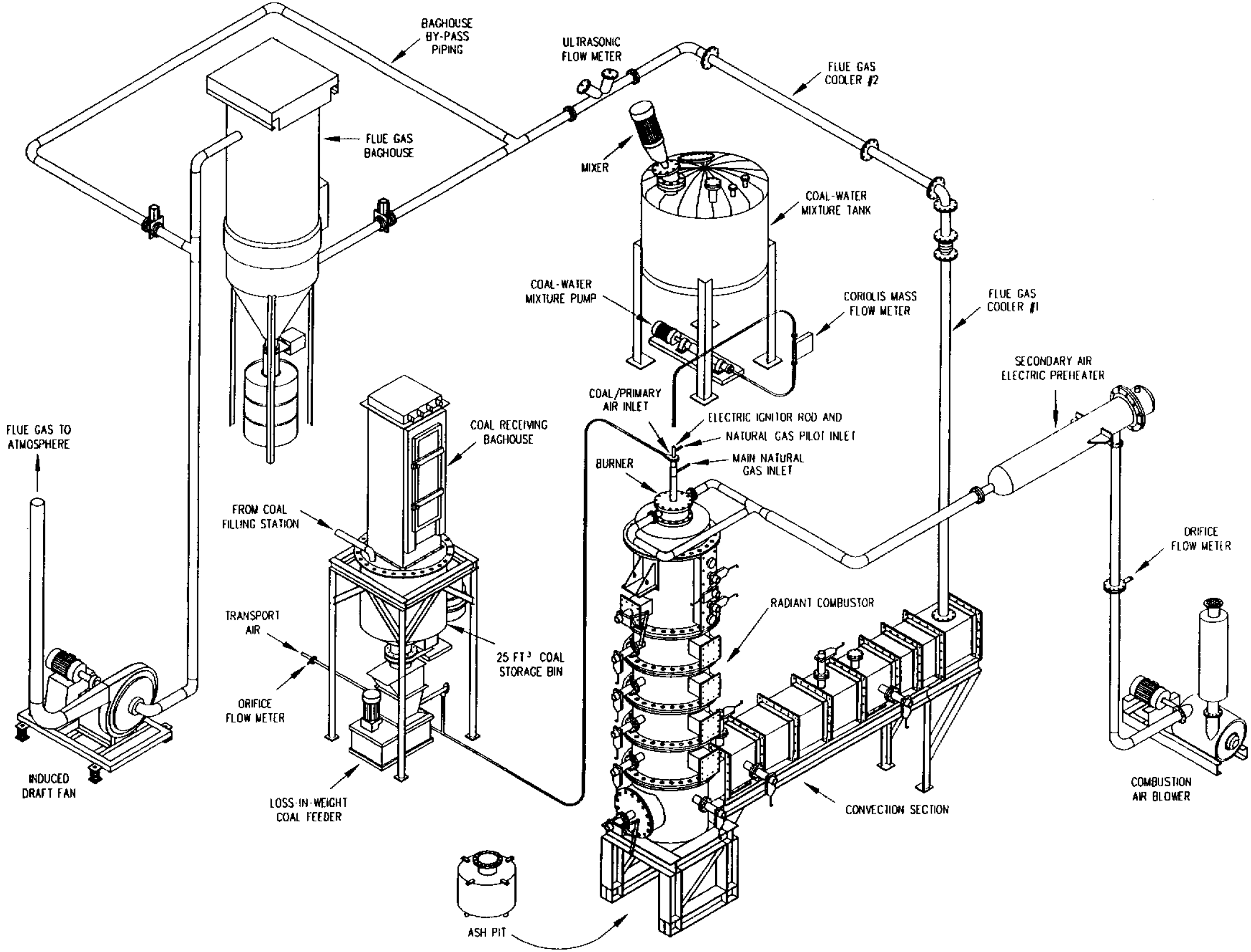

Figure 1: Combustion and Environmental Research Facility (CERF) of the U.S. DOE Federal Energy Technology Center