USDOE/EPRI BIOMASS COFIRING COOPERATIVE AGREEMENT

Quarterly Technical Report

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ABSTRACT

During the period of July 1, 2000 through September 30, 2000, alternatives for relocating the Seward Generating Station cofiring project were investigated. Allegheny Energy Supply Company LLC will accept the separate injection demonstration at its Albright Generating Station. During this period, also, efforts were made at program outreach. Papers were given at the Pittsburgh Coal Conference.

This report summarizes the activities during the second calendar quarter in 2000 of the USDOE/EPRI Biomass Cofiring Cooperative Agreement. It focuses upon reporting the results of the relocation of Seward, and on the outreach efforts

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TABLE OF CONTENTS

CONTENTS **Page #**

TABLES Page

FIGURES Page

EXECUTIVE SUMMARY

The sixteenth Quarter of the USDOE-EPRI contract, July 1, 2000 through September 30, 2000 was characterized by continued activities in disseminating information concerning the successes of the cofiring program. A major paper was given at the Pittsburgh Coal Conference concerning commercializing the cofiring process. Additionally, progress was made concerning relocating the separate injection cofiring project from Seward Generating Station to the Albright Generating Station of Allegheny Energy Supply Co., LLC. Activities in support of relocating this demonstration included discussions with Allegheny, a reallocation of USDOE-EPRI Cooperative Agreement funds, construction of a Memorandum of Understanding (MOU) between EPRI and Allegheny to support the relocation and completion of this demonstration, and supporting activities.

INTRODUCTION

Cofiring—the firing of two dissimilar fuels at the same time in the same boiler—has been proposed for using biomass in coal-fired utility boilers. In practice, this cofiring introduces a family of technologies rather than a single technology. The family of technologies includes blending the fuels on the coal pile or coal belt, and feeding them simultaneously to any processing (e.g., crushing and/or milling) systems on their way to the boiler; preparing the biofuels separately from the coal and introducing them into the boiler in a manner that does not impact fossil fuel delivery; or converting the solid biofuels to some other fuel form (e.g., producer gas) for firing in a coal-fired or natural gas-fired installation.

The practice of cofiring biofuels with coal, or blending biofuels with other opportunity fuels to be used in coal-fired generating stations, has reached a new stage in its commercialization process. Demonstrations are underway for cofiring with separate wood feeding at a wall-fired boiler—the Seward Generating Station of GPU Genco. Demonstrations also are underway for cofiring biomass with petroleum coke in a cyclone boiler—the Bailly Station #7 boiler of NIPSCO. More utilities are expressing interest in cofiring. Still others are beginning the process of investigating this technology.

Cofiring is often recognized as the least cost form of "green power" available to utilities which have access to a wood products industry, a furniture industry, a home construction industry, and/or the "urban forest" of broken pallets, tree trimmings, and the like. The Wisconsin Renewable Portfolio Standard explicitly recognizes cofiring of residues as an acceptable form of green power and renewable energy. Similarly, New Jersey recognizes the combustion of residues as renewable energy. Cofiring is also considered to be potentially a major contributor to fossil CO_2 reductions.

USDOE and EPRI developed a cooperative agreement to support the commercialization of this family of technologies. Some 16 projects have been developed as part of this program, as summarized below. As noted in the Executive Summary, several of these tasks have been completed or cancelled.

1. <u>Combustion Tests at GPU's Seward Plant (30 MWe, PC)</u>

   EPRI and GPU (an EPRI member utility operating the Seward power plant near the Johnstown, Pennsylvania headquarters of GPU's Penelec system) will arrange for other cofunding to augment USDOE's cofunding and will conduct a test of mid-level cofiring in a wall-fired PC unit using separate feed for the wood (i.e., not fed through the pulverizers along with the coal, as was done in the recent test cosponsored by USDOE, EPRI, GPU and the State of Pennsylvania at Penelec's Shawville plant in November 1995). This program also includes a long-term demonstration of cofiring at the Seward Generating Station, as a logical extension of the parametric performance testing.

This project is being relocated.

2. Fuel Preparation Tests at NYSEG's Greenidge Plant (100 MWe, PC)

EPRI is cosponsoring New York State Electric and Gas Company (NYSEG)—now AES—in a test program that focuses on the preparation of wood fuel for cofiring in a tangentially fired PC unit with separate feed for the prepared wood fuel. Size reduction equipment, such as wood "grinders" or hammermills, and drying equipment will be evaluated, and the suitability of the prepared product tested in full-scale com- bustion in the 100 MWe boiler at NYSEG's Greenidge plant. Mid-level, i.e., about 10% by heat, cofiring is planned.

This project has been terminated, unless significant changes occur in the approach taken by AES.

3. Pre-commercial Test Runs at TVA (~200 MWe)

EPRI is cosponsoring the next testing program at TVA, this one being the long-term "pre-commercial" test runs to cofire wood at levels up to 10% by heat, starting at the cyclone plant (Allen) in Memphis, and continuing at one of TVA's pulverized coal plants. This program includes considering gasification as a basis for cofiring, using the producer gas from biomass as additional fuel injected in the primary furnace.

4. Switchgrass Cofiring with Madison Gas & Electric (50 MWe)

EPRI is cofunding the University of Wisconsin at Madison in a test program being conducted by the University and the local utility (Madison Gas and Electric) at MG&E's Blount Street Station, where an existing retrofit to burn refuse-derived fuel (formerly) and shedded paper waste (currently) in a wall-fired PC unit is to be used to conduct the first U.S. test of cofiring switchgrass along with coal in a full-size utility boiler.

This task has been completed.

5. High-level Cofiring with Southern Company (50 MWe)

Southern Company Services has discussed with EPRI a potential cosponsored project to do long-term testing of high-level (i.e., up to 40% by heat) cofiring of wood with coal, perhaps with some natural gas overfire, in a tangentially-fired PC boiler in Savannah, Georgia. This project would be a follow-up to an initial set of short test runs there in 1993, which indicated that separate feed of this much wood was possible. This test will provide the opportunity to explore the upper limits of cofiring wood with coal in an existing PC boiler. This project also includes demonstration and testing of the entire fuel cycle for switchgrass as a biofuel. It includes growing and harvesting the switchgrass, milling this biofuel, and then cofiring it with coal in both the Southern Research Institute test combustor and then the 60 MW_e Gadsden Station of Alabama Power.

Support for this program has been provided. Further support is not anticipated at this time.

6. Study and Testing with NIPSCO (~500 MWe, Cyclone)

EPRI is completing a study, cofunded by EPRI and Northern Indiana Public Service Company (NIPSCO), to evaluate the fuel supply and the power plant operations for cofiring wood in a full-size cyclone boiler as one of NIPSCO's voluntary measures to reduce emissions of fossil CO_2 under the Climate Challenge program of the federal government. The next phase, assuming the expected favorable findings that cofiring is a low-cost CO_2 mitigation measure, is to be a cofunded test at, perhaps, NIPSCO's Michigan City plant, where manufacturing process waste wood is the expected source of relatively dry wood already at small size and with potential for a 5% by heat cofiring operation in an urban area outside of the normal wood products regions of the South, Upper Midwest or Pacific Northwest. This program also includes demonstrating the results of cofiring testing, over a longer term, at Bailly #7, another NIPSCO cyclone boiler.

7. Switchgrass Test with Nebraska Public Power District

One of EPRI's members, the Nebraska Public Power District (NPPD), has expressed interest in a preliminary evaluation of switchgrass cofiring, an evaluation that can be performed without commitment to a full-size unit test. EPRI has suggested to NPPD an evaluation based on laboratory testing at the Sandia National Laboratory's Combustion Research Facility in Livermore, California. With USDOE cofunding this would test the ability of the well-controlled, well-monitored test facility at Sandia to provide data and analysis capable of predicting the potential for the fouling of superheater tubes by the cofiring of high-alkali biomass, namely switchgrass, with coal. Combined with (1) the Madison test (Item 4, above), in which NPPD will participate, and (2) the series of tests done by Sandia on both biomass fuels and coals for DOE, NREL, USDOE, EPRI and industry during the past three years, and (3) USDOE's in-house testing of switchgrass/coal cofiring at CERF, this new project is expected to reveal the potential and the limits of laboratory testing as a facilitator of decisions on biomass cofiring.

This task has been cancelled.

8. Waste Plastics Cofiring with Duke (50-200 MWe, PC)

EPRI, Duke Power Company (Duke), and the National Plastics Council have cosponsored a laboratory test and engineering analysis of the cofiring of clean plastic manufacturing wastes with coal in a PC boiler. The next step is a unit test at full-size in a PC boiler, perhaps at 50 MWe or perhaps up in the 200 MWe range, approximate size. While actual biomass cofiring, i.e., waste wood cofiring, may or may not be part of the first unit tests, this project is important for the future of biomass cofiring because it involves a major investor-owned, coal-firing utility, located in a region of a major wood-products industry as well as major, and changing, agricultural and meat/poultry industries, as well as textile industries. It is an excellent test of waste cofiring justified on purely business grounds (fuel savings and customer service) but with potential to move toward environmental grounds, if warranted.

This task has been completed.

9. Plastic/Fiber/Pulp Wastes with SCE&G (~100 MWe, PC)

EPRI has discussed possible follow-on testing with South Carolina Electric and Gas Company (SCE&G), tests that would be a follow-on to a test run in 1993 where mixed plastic and wood fiber were fired with coal to determine technical feasibility for disposal of an industrial customer's manufacturing residues. Other residues, consisting primarily, or entirely, of pulp wastes rather than plastic may be tested next. Or, a second test, longer and with more variations, using the same plastic/ fiber residue may be the prime focus. The rationale for this as a biomass cofiring test is similar to that for Duke (a neighboring utility in the same wood industry region), but the scope is more directly on biomass, as well as plastic, as fuel, and the options for boiler retrofit may be different.

This task has been cancelled.

10. Urban Wood-Waste Study and Test in Pittsburgh

USDOE has suggested that EPRI join an evaluation of the urban wood waste resource in the industrial/commercial/residential region of Pittsburgh and environs. Course, low-cost or no-cost wood wastes would be fired with coal in a stoker boiler at the Bellefield Boiler Plant owned by a consortium that includes the University of Pittsburgh. The University would oversee and monitor a long-term test of low-level (about 2% by heat) cofiring of urban wood wastes (including tree trimmings) together with coal. The key elements of the test would be off-site wood processing, assessment of the urban wood supply and cost by means of actual fuel procurement, and, perhaps, assessment of fines separation and separate cofiring of fines in a normal utility boiler (i.e., PC or cyclone).

This task has been completed.

11. Toxic Emissions

Both EPRI and USDOE have measured trace emissions and effluents from the combustion of coal and from ash resulting from coal combustion. In this new project, EPRI and USDOE will combine their respective data sources, test facilities and expertise in an effort to determine the extent of trace emissions or effluents from the cofiring of wood or other biomass wastes with coal. After an evaluation of data on fuels and control processes, including data on fuel chemistry, ash chemistry, emissions, emission control systems, liquid waste streams and solid waste streams, EPRI and USDOE will plan and conduct a test to measure and/or predict the emissions, if any, of toxic species that may arise from cofiring biomass with coal. This project will explicitly consider a test at the ECTC (Environmental Control Test Center) at the Kintigh power station operated by NYSEG near Buffalo, New York. The best site and fuel combination for a test will be identified and a test will be conducted, if the evaluation indicates that a useful measurement of toxic emissions can be obtained.

This task has been cancelled.

12. <u>Fuel/Powerplant Models, Analysis and Interpretation</u>

In order to interpret results from this entire set of projects and to facilitate the transfer of the results to the industry, EPRI will develop a SOAPP ("State-of-the-Art Power Plant") module for evaluating wood cofiring situations. SOAPP already has modules for combustion turbine power systems, and SOAPP modules for conventional utility PC and cyclone plants, and also FBC and coal gasification systems, are under development. By July 1996, the first SOAPP cofiring module will be completed, for natural gas as the cofired fuel in a reburn or other mode. This new project (No. 12 of the USDOE/EPRI cofiring program) will add wood cofiring to SOAPP, and also will add a fuels database capable of putting the properties of each new cofiring fuel into a context for comparison to some 50 other fuels and for prediction of slagging/ fouling/agglomeration potential in comparison to those other fuels. The result will be a model that will make possible the interpretation of test results from all the cofiring experiments in terms of the performance and cost impacts on a state-of-the-art coal-fired powerplant. Currently, but separate from this proposal, EPRI and USDOE are cooperating on the EPRI-developed CQIM computer model by doing tests to obtain data on slagging/fouling for blends of coals. This work will be used and expanded under this USDOE/EPRI biomass cofiring project. EPRI's fuels database for biomass and other alternative fuel properties (including slagging indices, etc.) will be incorporated into CQIM, SOAPP and other analytical frameworks as appropriate. EPRI's biomass resource assess-ments and tools for developing supply/cost curves will be applied as appropriate to address regional or local biomass resource issues important to USDOE.

This task has been cancelled and the funds have been redirected to the relocation of the Seward Cofiring Demonstration.

13. CO_2 Utilization in Algal Systems for Wastewater Treatment

EPRI and USDOE have independently done experiments and studies of systems that can take advantage of the high rates of capture of CO_2 by aquatic biological systems such as seaweed (kelp), microalgae (ocean and land-based) and halophyte species (both in water and on dry land). This new project under this USDOE/EPRI cofiring project will assess what appears to be one of the few near-term options for an algae-based system to contribute to reductions of CO_2 emissions: the use of CO_2 to speed the growth of algae in water treatment facilities. This approach adds a coproduct value, namely the improved performance of the water (i.e., sewage) treatment plant, that may make the system one of the low cost options for near-term CO_2 mitigation. Two forms of fossil CO_2 reduction are involved: (1) capture of CO_2 into a biomass form, i.e., a process similar to carbon sequestration in forest biomass, but in this case coupled directly to use of a CO_2-enhanced stream like powerplant fluegas; and (2) replacement of a fossil fuel by a biomass fuel, as the algae grown with the enhanced CO_2 stream replace fossil fuel, i.e., a process similar to the CO_2 recycling inherent in all uses of biomass fuels replacing fossil fuels.

This task has been completed.

14. Combustion Tests and Combustor Development

EPRI and TVA have sponsored an initial assessment of slagging com-bustion as a way to use high-alkali biomass as fuel in power generation without having to solve the problems associated with gas cleanup to meet the purity required by the gas turbines in biomass gasification combined cycle power systems. USDOE has completed the first in a planned series of bench-scale tests of the cofiring of high-alkali fuels with coal in CERF (Combustion Environment Research Facility) at USDOE. This new project in the USDOE/EPRI cofiring program will use test systems at USDOE to obtain data to predict performance and guide design for use of high-alkali biomass fuels in mid- to high-level fractions (approximately 20% to even 100% of the heat into a coal-fired power system). The new project will start with follow-up design and fuel/ash studies that apply and interpret relevant work already completed. Tests will be planned and performed as appropriate, in accord with assessments and plans prepared by EPRI and USDOE staff and contractors, and in accord with an implementation plan approved by USDOE.

This task has been cancelled.

15. Ash Sales

An immediate barrier to the cofiring of biomass with coal in existing coal-fired powerplants is the potential that the flyash from the cofired operation of the plant will not be purchased by the cement industry, which is now the best market for flyash from coal-fired utility boilers. This project will develop and communicate an action plan that will enable a cement industry standards board to make as early as possible a finding that cofired ash is acceptable for purchase from utility powerplants.

This task has been cancelled.

16. CO_2 Capture and Disposal

This project will conduct a series of feasibility studies of various proposed options for capture and disposal of carbon dioxide from U.S. coal-fired power plants. Consideration will be given to both land and ocean-based disposal options in an effort to determine which options would be most amenable to fossil carbon sequestration for both existing and future U.S. power generation capacity. This effort will build on the results of studies previously performed by the International Energy Agency (IEA) Green-house Gas Research and Development Program with joint DOE and EPRI funding.

This task has been completed.

TECHNICAL PROGRESS

Project 1 – Combustion Testing at the Seward Generating Station

Allegheny Energy Supply Company, LLC. agreed to host the separate injection cofiring demonstration at Boiler #3 of the Albright Generating Station. Boiler #3 is a 150 MW_e tangentially-fired (T-fired) unit equipped with low-NO_x firing and separated overfire air. Separate injection cofiring of sawdust, or any other biomass fuel, has not been tested or demonstrated in any coal-fired unit equipped with separated overfire air. Consequently the Albright test program will provide key insights into the usefulness of cofiring for NO_x control in units equipped with low NO_x firing technologies.

In pursuit of this relocation, several actions were taken:

- The demonstration was moved to direct funding from USDOE to Allegheny Energy Supply Co., LLC on a cost-sharing basis. EPRI is now responsible only for funding the testing portions of the program that focus on emissions management through cofiring.
- A memorandum of understanding between EPRI and Allegheny was constructed facilitating removal of the equipment from Seward Generating Station, and relocation of that equipment to Albright.
- Allegheny retained Foster Wheeler to manage the relocation and the installation at Albright Generating Station, thereby maintaining program continuity.

The relocation and continuation of this demonstration is now assured. Further, because of the configuration of the boiler, there will be increased information concerning the flexibility and utility of biomass cofiring as a NO_x control strategy.

Project 2 – Fuel Preparation Tests at Greenidge Generating Station

This project remains outside the cooperative agreement at this time due to business decisions by AES.

Project 3 – Precommercial Testing and Gasification Investigation at TVA Fossil Plants

TVA has continued to evaluate its options regarding cofiring, including gasification.

Project 4 – Switchgrass Testing at Blount St. Station of Madison Gas & Electric

This project was completed.

Project 5 – High Percentage Cofiring with Southern Company

No operational activity occurred on this project

Project 6 – Cofiring Testing at Michigan City Generating Station of NIPSCO, and Demonstration of Cofiring at that Utility

No operational activity occurred on this project

Project 7 – Testing Cofiring of Switchgrass by Nebraska Public Power District/Sandia

This project was cancelled.

Project 8 – Waste Plastics Cofiring at Duke Power

This project was cancelled.

Project 9 – Plastics/Fiber/Pulp Waste Cofiring with SCE&G

This project was cancelled.

Project 10 – Urban Wood Waste Cofiring in Pittsburgh, PA

This project was completed.

Project 11 – Toxic Emissions from Cofiring Evaluation

This project was cancelled.

Project 12 – Fuel/Powerplant Model Development

This project was cancelled and the funds were redirected towards the relocation of the Seward project.

Project 13 – CO_2 Utilization in Algal Systems

This project has been completed.

Project 14 – Combustion Tests and Combustor Development

This project was cancelled.

Project 15 – Support for Ash Sales from Cofiring Plants

This project was cancelled.

Project 16 – CO_2 Capture and Disposal Options

This project has been completed.

ATTACHMENTS

COFIRING BIOMASS WITH COAL: ISSUES FOR TECHNOLOGY COMMERCIALIZATION

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ABSTRACT

Cofiring biofuels with fossil fuels for electricity generation has been under development since 1992. Initial programs blended wood waste with coal on the coal pile for both cyclone and pulverized coal (PC) boilers, or separately injected sawdust into tangentially-fired and wall-fired PC boilers. Such programs have been conducted at TVA, Southern Company, Northern Indiana Public Service Company (NIPSCO), New York State Electric and Gas, and GPU Genco (now Sithe Energies). More recent programs at GPU Genco, NIPSCO, Southern Company, Alliant Energy, and Allegheny Power Company have investigated and/or tested cofiring with more advanced concepts including blending biofuels with other opportunity fuels to design alternative energy sources for cyclone boilers, firing switchgrass and other agricultural products in PC boilers using separate injection, designing burners explicitly to optimize cofiring, and gasifying biomass in order to integrate biofuel cofiring into natural gas-fired electricity generating settings. This paper focuses upon some fundamental fuel composition and associated combustion chemistry considerations to consider recent results from cofiring programs, and to examine some of the opportunities and technical issues associated with cofiring.

1.0. INTRODUCTION

Cofiring is generally viewed as the most cost-effective approach to biomass utilization by the electric utility industry. Originally, cofiring was introduced as a means for utilities to accomplish the following objectives:

- support economic development among wood products and agricultural industries in a given service area;
- reduce fossil CO_2 emissions as part of the voluntary global climate challenge program
- reducing other airborne emissions including oxides of nitrogen (NO_x) and trace metals
- provide a means for transitioning to a broader base of biofuel supplies by developing infrastructural support for fuel supply and delivery.

The advent of deregulation, coupled with State and Federal efforts to encourage the use of renewable resources, has led to additional forces promoting the use of biofuels for electricity generation including proposed portfolio standards (now law in New Jersey), proposed tax incentives for generating power with biomass (e.g., 1¢/kWh), the initiation of "green power" sales programs, and related efforts. At the same time, however, deregulation increased pressures on utilities to maximize the efficiency of boiler operations, and to minimize fuel costs.

2.0. TECHNOLOGY OPTIONS FOR COFIRING

Cofiring is a family of technologies. These include blending biomass with coal on the fuel pile, separately injecting biomass into a boiler, and gasifying biomass for subsequent firing in an electricity generating system.

2.1. Blending biomass with coal on the fuel pile.

This simple approach to blending biomass with coal for subsequent introduction into the boiler is the first and least cost approach to cofiring. This can be accomplished at low percentages (e.g., <5 percent by mass, depending upon pulverizer type) in pulverized coal (PC) boilers when wood waste is the biofuel. It can be accomplished at higher percentages, typically up to about 20 percent by mass, when applied to cyclone boilers. When this approach to cofiring is employed in PC boilers its most significant impact on the pulverizer. The addition of wood waste to the coal feed increases pulverizer amps, and impacts feeder speeds on table feeders for ball and race mills. It decreases mill outlet temperatures on bowl mills. Both of these limit the percentage of biomass that can be added to the total fuel blend at very low levels; alternatively these impacts cause a derating of the mills and, if mill capacity limits boiler capacity, this approach can cause a derating of the boiler.

When blending biomass with coal on the coal pile it is important to note that the type of biomass is limited. Bark can cause significant problems because it can be very stringy. It can cause mill problems. Switchgrass and straws, when chopped to particles typically 25 – 50 mm (1 – 2 in) in length can cause pluggage in the bunkers—even when only 5 percent straw or switchgrass is employed in the blend on a mass basis. Note that these biomass forms are typically on the order of 80 kg/m^3 (5 lb/ft^3), while coal is on the order of 881 kg/m^3 (55 lb/ft^3). A 5 percent straw/95 percent coal blend on a weight basis is about a $1m^3$ straw/$1.7m^3$ coal blend. The blend is 37 percent straw or switchgrass on a volumetric basis.

Some early experiments documented degradation in sieve analysis when cofiring percentages >5 percent on a mass basis were employed. Work by TVA documented that bowl mills can handle up to 5 percent sawdust on a mass basis while maintaining a coal product with >70 percent fuel <200 mesh in particle size. Cofiring percentages above 5 percent wood waste on a mass basis resulted in less than acceptable sieve analyses.

This cofiring technique is more appropriate to cyclone boilers, where pulverizers are not employed, and where the coal is typically crushed to 6 mm x 0 mm (¼" x 0") in particle size and then fired directly into the cyclone barrel. The capacity limiting issue is the speed of the cyclone feeder. If the cyclone boiler has been converted from bituminous coal to Powder River Basin (PRB) coal, capacity can be at issue. In cyclone firing, this approach lends itself to a practice of blending the biomass with another opportunity fuel—petroleum coke, tire-derived fuel, etc.—and firing the blend in the boiler to achieve multiple objectives.

2.2. Cofiring with separate injection.

This approach involves separately preparing the biomass—sawdust, switchgrass, etc.— and then firing it in the boiler. In this approach, the biomass bypasses the pulverizers. It may be introduced into the burner or in a separate injection point in a wall-fired PC boiler. If the boiler is tangentially fired (T-fired), the biomass may be blown directly into the furnace. A T-fired boiler can be viewed, conceptually, as a single burner with multiple injection points. The biomass is introduced simply at another injection point in the furnace (or burner). In making such an injection, the local stoichiometry can be altered somewhat depending upon the air/fuel ratio in the biomass injection system. This approach involves more equipment than blending on the coal pile, however it can accomplish higher percentage cofiring in PC boilers. It can be used for NO_x reduction. It can also be used for capacity recovery if wet coal and pulverizer capacity limit the steaming rate of the boiler.

Cofiring with separate injection requires careful attention to biomass particle size. Testing at Greenidge Station, Seward Generating Station, and Plant Kraft all document that the kinetics of biomass combustion are far more rapid than the kinetics of coal combustion. Consequently particles typically <3 mm (1/8") and, to a large extent <6 mm (¼") can be fired successfully in such systems. Tests by Madison Gas & Electric, and demonstrations in Europe, document the fact that straws and switchgrass can be fired if particle lengths are <50 mm (2"). Cofiring with separate injection involves more careful attention to fuel preparation. It also requires attention to the interplay between fuel preparation and furnace residence time. These parameters, however, have been readily managed at all cofiring demonstrations to date.

2.3. Gasification-based cofiring

The gasification approach to cofiring has significant potential, for it permits the use of biomass in natural gas-fired systems: boilers and CCCT installations. Gasification-based cofiring has been demonstrated in Lahti, Finland. In gasification-based cofiring, biomass is first fed to a gasifier in order to generate a producer gas typically containing about 50 percent N_2 (volumetric basis) along with a mixture of CO, CO_2, CH_4, $C_2H_{2\text{-}6}$, H_2, and H_2O. Minor concentrations of tars and other condensables are formed in the gasification process as well. The heating value of this gas depends upon the moisture content of the feedstock. The gas is then fired in a boiler or in a duct burner between a combustion turbine and a heat recovery steam generator or a waste heat boiler in a CCCT application.

Gasification-based cofiring addresses several issues commonly associated with cofiring including accomplishing complete combustion in a furnace with a very short gas residence time, separating biomass ash from coal ash, and providing a means for cofiring in natural gas-fired electricity generating systems. While it is the most capital intensive approach to cofiring, it is also the most flexible in terms of the base fuel considered (coal, oil, natural gas) and the electricity generating system appropriate to its application.

3.0. COFIRING EXPERIENCE IN THE USA

Given the various techniques for cofiring within this technology family, it is useful to consider the experience of utilities pursuing this approach to biomass utilization in the USA and in Europe. This experience is based upon programs sponsored by the US Department of Energy (USDOE) through the Office of Energy Efficiency and Renewable Energy (EERE), National Energy Technology Laboratory (NETL), National Renewable Energy Laboratory (NREL), and Electric Power Research Institute (EPRI).

3.1. Initial Test Experience

In 1992, the Tennessee Valley Authority (TVA), together with the Electric Power Research Institute (EPRI) and the US Department of Energy (USDOE), initiated engineering studies to determine the feasibility of installing cofiring systems at its fossil energy plants. These engineering studies led to testing at the Allen Fossil Plant, the Kingston Fossil Plant, and the Colbert Fossil Plant. Simultaneously, Southern Company initiated cofiring studies and tests at several of its generating stations including Plant Hammond, Plant Yates, and Plant Kraft. Subsequently, General Public Utilities (GPU) evaluated cofiring at its western Pennsylvania generating stations and tested cofiring at its Shawville and Seward Generating Stations. Northern Indiana Public Service Company (NIPSCO) analyzed cofiring at its cyclone boilers and tested this concept at its Michigan City Generating Station. Madison Gas and Electric tested cofiring switchgrass at its Blount St. Station, and other utilities also evaluated cofiring either through engineering studies, parametric tests, or a combination of the two. Table 1 summarizes some of the key parametric test experience in cofiring of biomass with coal.

Conclusions derived from the parametric testing of boilers identified in Table 1, including the commercializing of cofiring at several locations, include the following:

- blends of wood waste and coal will flow through bunkers to pulverizers or cyclone feeders with minimum bridging;
- blends of wood waste and coal can be stocked out and stored through summer months and, if the piles are constructed correctly, spontaneous combustion will not occur
- blends of wood waste or switchgrass and coal can be burned with minimum impact on boiler operations—the blend may be largely transparent to the boiler operator

- there are no technical show stoppers to cofiring biofuels with coal in existing boilers, although there are efficiency and emissions impacts and there can be capacity impacts.

Table 1. Identification of Representative Major Cofiring Tests and Demonstrations

Utility	Generating Station	Cofiring Approach	Boiler Capacity	Coal Type	Biomass Type
TVA	Allen (cyclone)	Blending biomass & coal; 5-20% by mass	272 MW_e	Illinois basin, Utah bituminous	Wood waste
TVA	Kingston (T-fired PC)	Blending biomass & coal; 1-5% by mass	190 MW_e	Eastern bituminous	Wood waste
TVA	Colbert (wall-fired PC)	Blending biomass & coal; 1-5% by mass	190 MW_e	Eastern bituminous	Wood waste
GPU Genco	Shawville (T-fired & wall-fired PC)	Blending biomass & coal; 3% by mass	190 MW_e 138 MW_e	Eastern bituminous	Wood waste, hybrid poplar
GPU Genco	Seward (wall-fired PC)	Separate injection of biomass	32 MW_e	Eastern bituminous	Wood waste
NIPSCO	Michigan City (cyclone)	Blending biomass & coal; 10% by mass	469 MW_e	PRB, Shoshone	Urban wood waste
MG&E	Blount St. (wall-fired PC)	Separate injection of biomass; 5-20% by mass	50 MW_e	Midwest bituminous	Switchgrass
NYSEG	Greenidge Station (T-fired PC)	Separate injection of biomass; 10-20% by mass	104 MW_e	Eastern bituminous	Wood waste
Southern	Plant Hammond (T-fired PC)	Blending biomass & coal; 5-14% by mass	120 MW_e	Eastern bituminous	Wood waste
Southern	Plant Kraft	Separate	55 MW_e	Eastern	Wood waste

	(T-fired PC)	injection of biomass; 20-50% by mass		bituminous	

Source: Tillman, Hughes, and Plasynski. 1999.

The parametric test experience further documented the following impacts when cofiring biomass with coal:

- reduced boiler efficiency, with the reduction being manageable
- reduced NO_x emissions, with reductions greater than originally expected
- reduced fossil CO_2 emissions, typically on the order of 2.7 – 3.15 tons fossil CO_2 avoided per ton of biomass burned(*)

The NO_x reductions exceed theoretical calculations as shown in Figure 1, based upon the test experience at the Allen Fossil Plant (Tillman et. al., 1996). Similar curves exist for Seward Generating Station. This improved NO_x control comes from the synergies between control mechanisms as explored in subsequent sections of this paper.

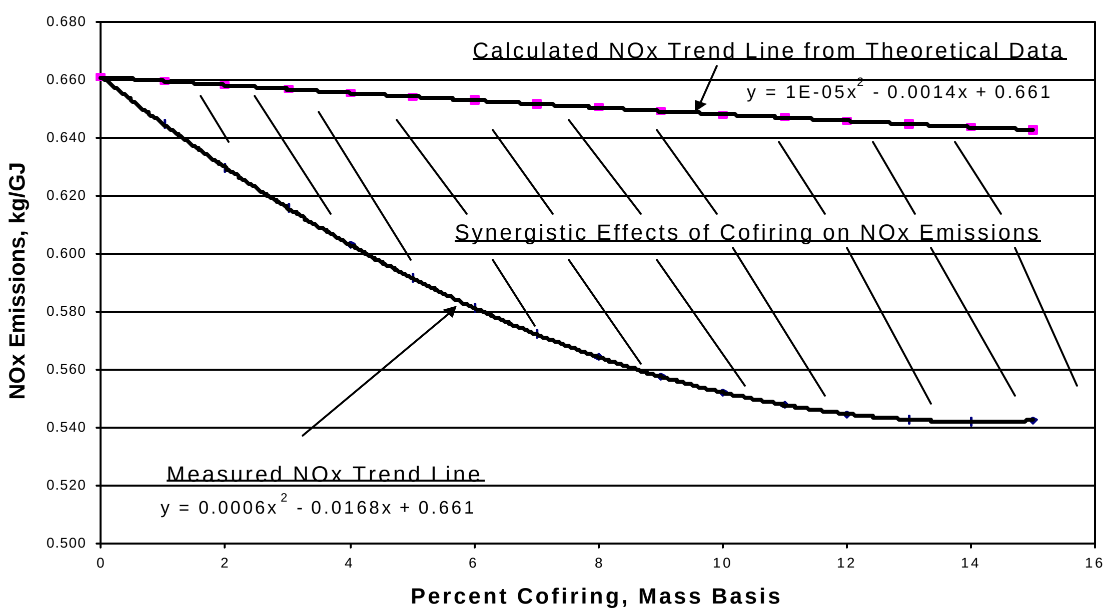

Figure 1. NOx Reductions at the Allen Fossil Plant, Comparing Theoretical Calculations to Measured Emissions.

NO_x reduction, then, became a significant additional factor supporting the cofiring of biomass in coal-fired utility boilers. Significantly, the mass percentage of biomass has more of an influence on NO_x reduction than the calorific percentage of biomass. This phenomenon is explored further in section 4 of this paper.

3.2. Commercial Demonstrations

The success of the parametric testing has led to commercial demonstrations at several locations including the Greenidge Station of New York State Electric and Gas (NYSEG)/AES, the Bailly Generating Station of Northern Indiana Public Service Company (NIPSCO) the Seward Generating Station of GPU Genco/Sithe Energies, and the Ottumwa Generating Station of Alliant Energy, under the Cheriton Valley RC&D switchgrass cofiring program. Cofiring demonstrations and commercial plants have also been established in several European countries.

Several of these demonstrations have been reported on previously (see, for example, Tillman and Hus, 2000; Tillman, Hughes, and Plasynski, 1999; Tillman and Battista, 1999). Further, they are summarized by Battista (2000) as presented in this conference. Results from these demonstrations confirm the earlier findings from the parametric tests. Further, they call attention to the need for investigations into the chemical composition and combustion characteristics of the various types of biomass with respect to the various ranks of coal.

4.0. FUELS AND COMBUSTION CONSIDERATIONS

The combustion consequences of cofiring are readily understood in terms of the fuel characteristics of the various fuels.

4.1. Characteristics of Coal and Biomass

Cofiring biomass in coal-fired boilers introduces a fundamentally different fuel into the furnace. Tables 2 and 3 present fuel analyses for selected biofuels and selected coals.

Table 2. Typical Fuel Analyses of Various Types of Biomass

Proximate Analysis (weight percent)	**Sawdust**	**Urban Wood Waste**	**Switchgrass**	**Alfalfa Stalks**
Fixed Carbon	9.34	12.5	12.19	15.62
Volatile Matter	55.03	52.56	65.19	68.06
Ash	0.69	4.08	7.63	5.84
Moisture	34.93	30.78	15.00	10.48
Ultimate Analysis (weight percent)				
Carbon	32.06	33.22	39.68	40.60
Hydrogen	3.86	3.84	4.95	5.15
Oxygen	28.17	27.04	31.77	36.02
Nitrogen	0.26	1.00	0.65	1.83
Sulfur	0.01	0.07	0.16	0.09
Ash	0.69	3.99	7.63	5.90
Moisture	34.93	30.84	15.00	10.48
Higher Heating Value (GJ/tonne)	10.39	11.07	12.62	13.59
Higher Heating Value (Btu/lb)	5431	5788	6601	7108
Volatile/Fixed Carbon Ratio	5.89	4.20	5.35	4.35

Table 3. Typical Fuel Analyses of Various Coals

Proximate Analysis (weight percent)	Black Thunder (PRB)	White Oak (Utah Bituminous)	Upper Freeport (Pennsylvania Bituminous)	Illinois #6
Fixed Carbon	34.94	43.34	56.76	44.98
Volatile Matter	30.72	38.23	22.69	35.32
Ash	5.19	7.84	13.03	7.43
Moisture	29.15	10.59	7.52	12.27
Ultimate Analysis (weight percent)				
Carbon	51.30	63.50	69.14	66.04
Hydrogen	2.87	4.37	4.04	4.38
Oxygen	10.46	12.24	2.54	5.66
Nitrogen	0.68	0.90	1.18	1.40
Sulfur	0.35	0.56	2.13	2.79
Ash	5.19	7.84	13.03	7.43
Moisture	29.15	10.59	7.52	12.27
Higher Heating Value (GJ/tonne)	17.00	22.00	23.02	22.44
Higher Heating Value (Btu/lb)	8888	11499	12035	11731
Volatile/Fixed Carbon Ratio	0.88	0.88	0.40	0.79

The biomass tends to have a modest heat content along with high volatility. The data in Tables 2 and 3 demonstrate that biomass may be lower or higher than coal in fuel nitrogen concentration, measured in kg/GJ (lb/10^6 Btu); and they may be lower or higher than coal with respect to ash concentration. Fuel sulfur is typically lower in biofuels than in coal.

4.2. Volatility of Biomass

Notice the relative volatility of the two types of fuel; the biomass has a volatile/fixed carbon (V/FC) ratio typically >4.0 and frequently exceeding 5.0. The V/FC ratio for coal is virtually always <1.0. Other opportunity fuels have widely varying volatility. TDF, for example, has a typical V/FC ratio of ~2.5 while petroleum coke can have a V/FC ratio on the order of 0.2.

It is important to note that practical volatility can be influenced by two factors: 1) fuel particle size, and 2) combustion temperature. Smaller particles will release more volatiles, and will release them more rapidly. Higher temperatures will also cause a greater proportion of the combustible fraction of a fuel to be released as volatiles, and lower temperatures will promote increased char formation.

The differences in fuel volatility—critical to the success of cofiring as an emissions reduction technique—are directly related to fuel architecture. If wood is used as an example of biofuels, then the architecture can readily be seen. Wood is comprised of polysaccharides or holocellulose (cellulose and the hemicelluloses), lignin, and extractives. Cellulose, the dominant polysaccharide, is composed of anhydroglucose units connected by 1→4-β-glucosidic linkages. The principal functional group is the –OH group. Upon oxidation, functional groups will include carbonyls, ketos, and carboxyls. Hemicelluloses are branched-chain polysaccharides. For hardwoods the principal component is 4-0-methylglucoronoxylan. For softwoods the principal component is glucomannan. Functional groups associated with the hemicelluloses include carboxyls, methyls, and hydroxyls (Tillman, Rossi, and Kitto, 1981). There are no aromatic components in the holocellulose. Figure 2 presents the traditional representation for the structure of cellulose, representing both cellulose and the hemicelluloses.

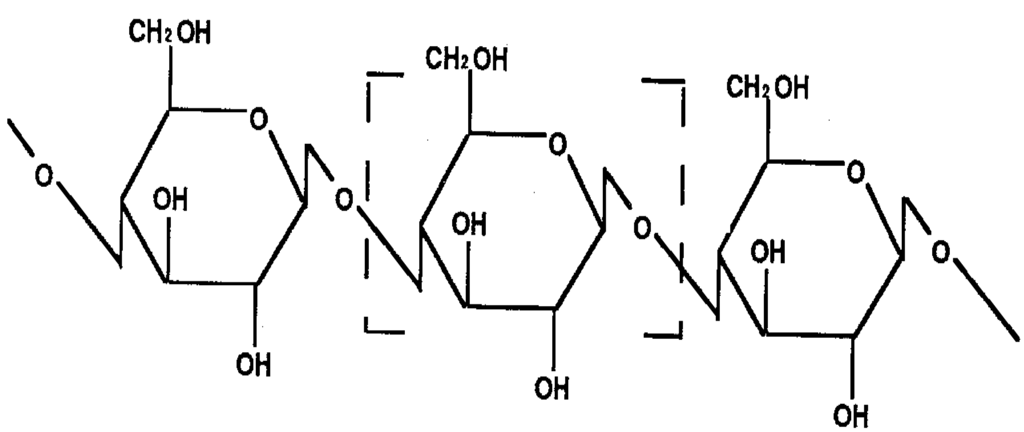

Figure 2. Structural Representation of Cellulose, Identifying the Glucose Molecule as the Basic Building Block.

Lignin, the lesser reactive material in biofuels, consists of a basic skeleton of four or more substituted phenylpropane units. The typical softwood lignin structure is based upon guaiacyl alcohol as the basic building block. Hardwood lignins are typically built from syringyl alcohol. Note that the aromatic rings exist as single units connected by extensive branching. Figure 3 presents a structural representation of softwood lignin.

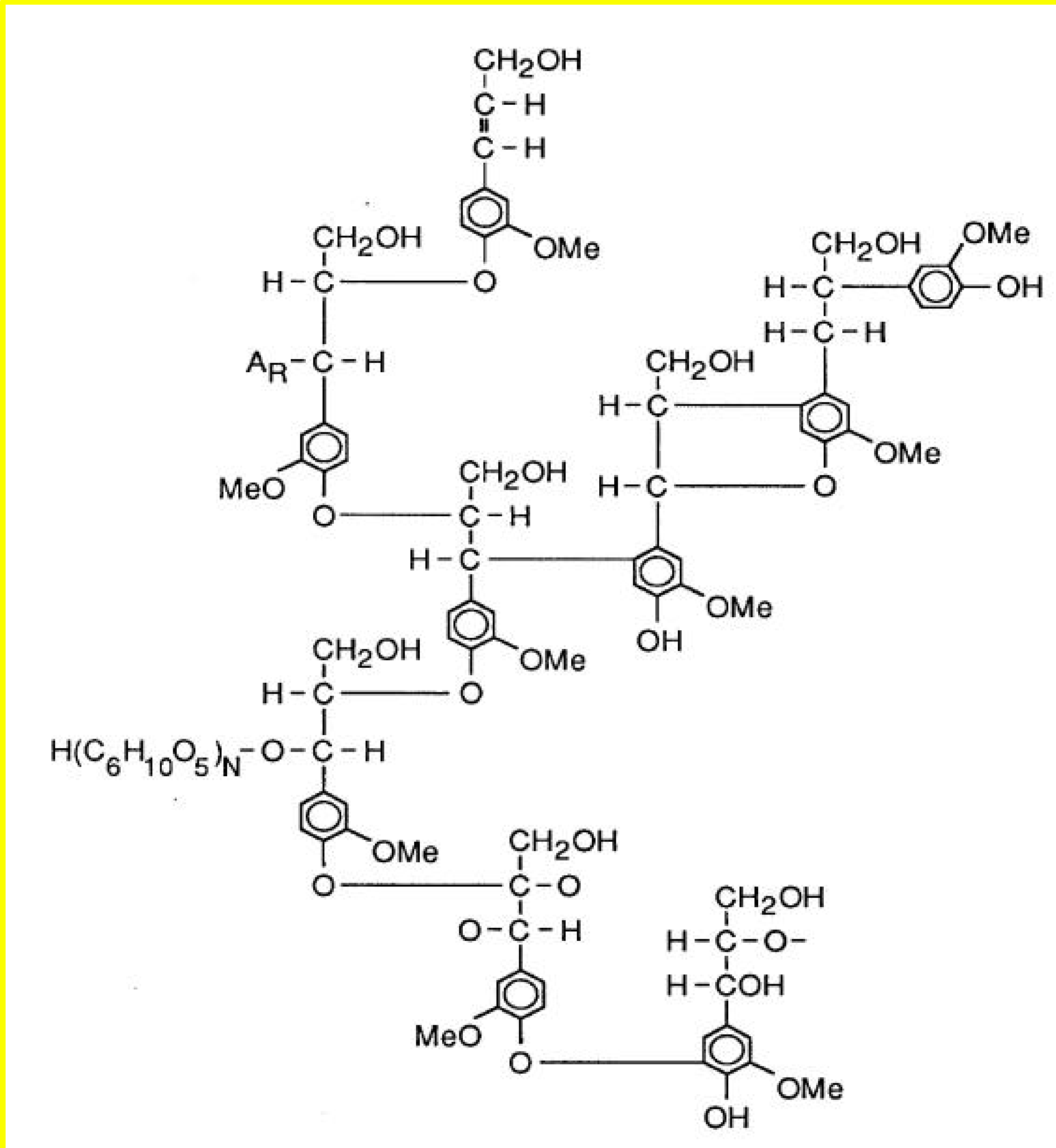

Figure 3. Structural Representation of Softwood Lignin Showing Placement of Aromatic Rings, Functional Groups, Bridges, and Linkages to Holocellulose (adapted from Adler, 1977).

Heteroatoms (e.g., N, Cl) are a function of living processes. Consequently the nitrogen exists as a consequence of protein structures in the inner bark of wood and in some lignin precursers, and virtually always in amine structures ($-NH_{1-3}$).

The many ranks of coal exhibit varying structures, however all are considerably more condensed than the components of the biofuels. Clusters of fused aromatic rings vary in size from 1 to 4 or 5 rings/cluster depending upon rank, as one moves from lignite to low volatile bituminous coal and anthracite coal. The oxygen contained in functional groups also changes to less reactive forms (e.g., from –OH functional groups to –O functionalities) as the rank of coal moves from the more reactive to the less reactive. Figure 4, a representation of subbituminous coal, was developed by Wiser as one of many potential representative structures for that fossil fuel. It highlights the clusters of aromatic rings, the diversity of functional groups and bridges, and the numerous forms of reduced nitrogen in coal.

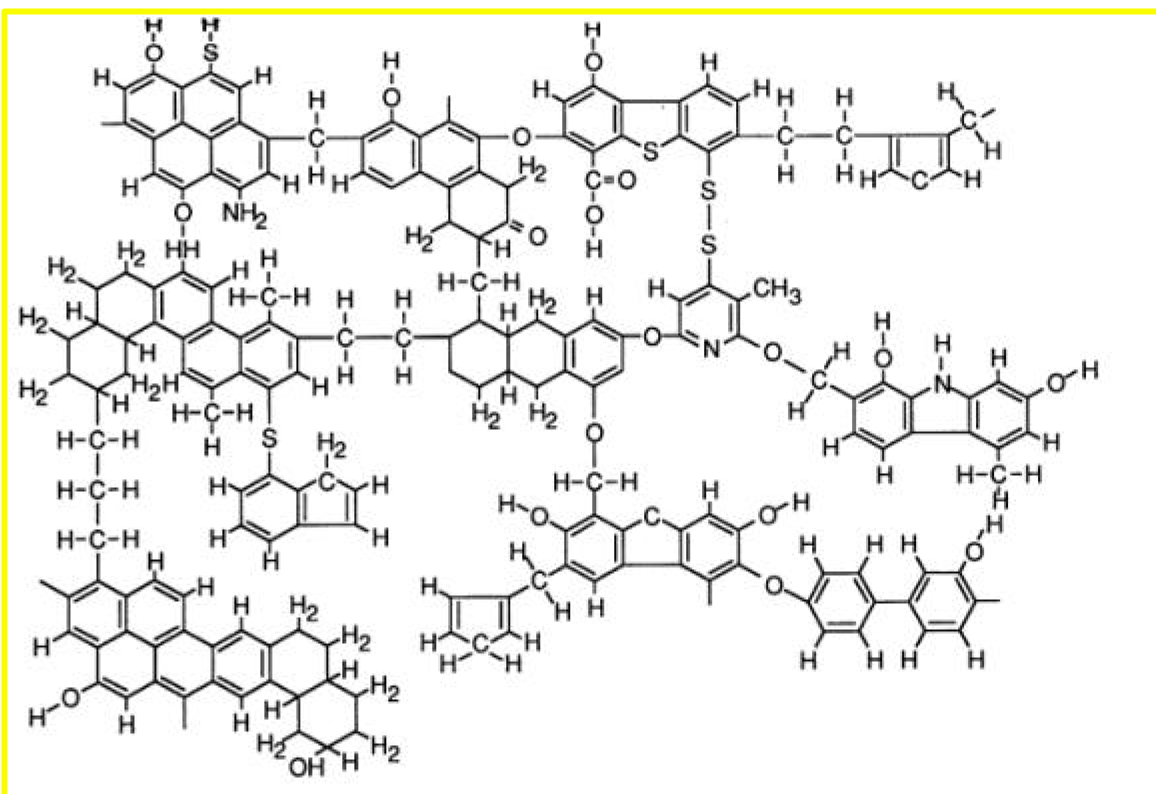

Figure 4. Structural Representation of Subbituminous Coal Developed by Wiser Showing Aromatic Clusters, Possible Functional Groups, and Bridges (National Research Council, 1977).

The structural comparisons can be made between the biofuels and coal with respect to aromaticity and nitrogen composition, as is shown in Table 4. Aromaticity, shown in Table 4, is a primary determinant of reactivity. The form of oxygen in a fuel is also a significant contributor to, and indicator of, reactivity. Van Krevelen and Schuyer (1957) have shown that the lower rank coals, with lower concentrations of carbon, have significant concentrations of oxygen in highly reactive forms: -COOH, $-OCH_3$, and -OH. These functional groups dominate the form of oxygen in low rank coals. Among the higher ranks of coal, the reactive -COOH and $-OCH_3$ functional groups are absent. Some -OH functionalities exist, however, in all ranks of coal. Comparisons to the representations in Figures 2 and 3 indicate that all of the highly reactive functionalities are common in the biomass oxygen.

Table 4. Aromaticity of Biomass and Coal

Fuel	Aromatic Rings Per Cluster in a Given Fuel				Percent of Carbon Atoms in Aromatic Rings
	1	2	3	4	
Woody Biomass	100	0	0	0	20 – 25
Texas Lignite	42	26	21	11	46
Wyoming Subbituminous	39	35	--	26	40
Illinois Bituminous	8	50	36	8	60 - 70
Anthracite	N/A	N/A	N/A	N/A	>90

Sources: Chung and Goldberg, 1988; Chung, Goldberg, and Ratto, 1987; Tillman, 1991

The volatility can then be viewed in terms of thermogravimetric analyses. These data generally indicate the high volatility of biomass fuels when compared to coals—even Powder River Basin subbituminous coals. Such analyses are presented in Figures 5 and 6. They compare sawdust to White Oak bituminous coal, a high volatile bituminous coal.

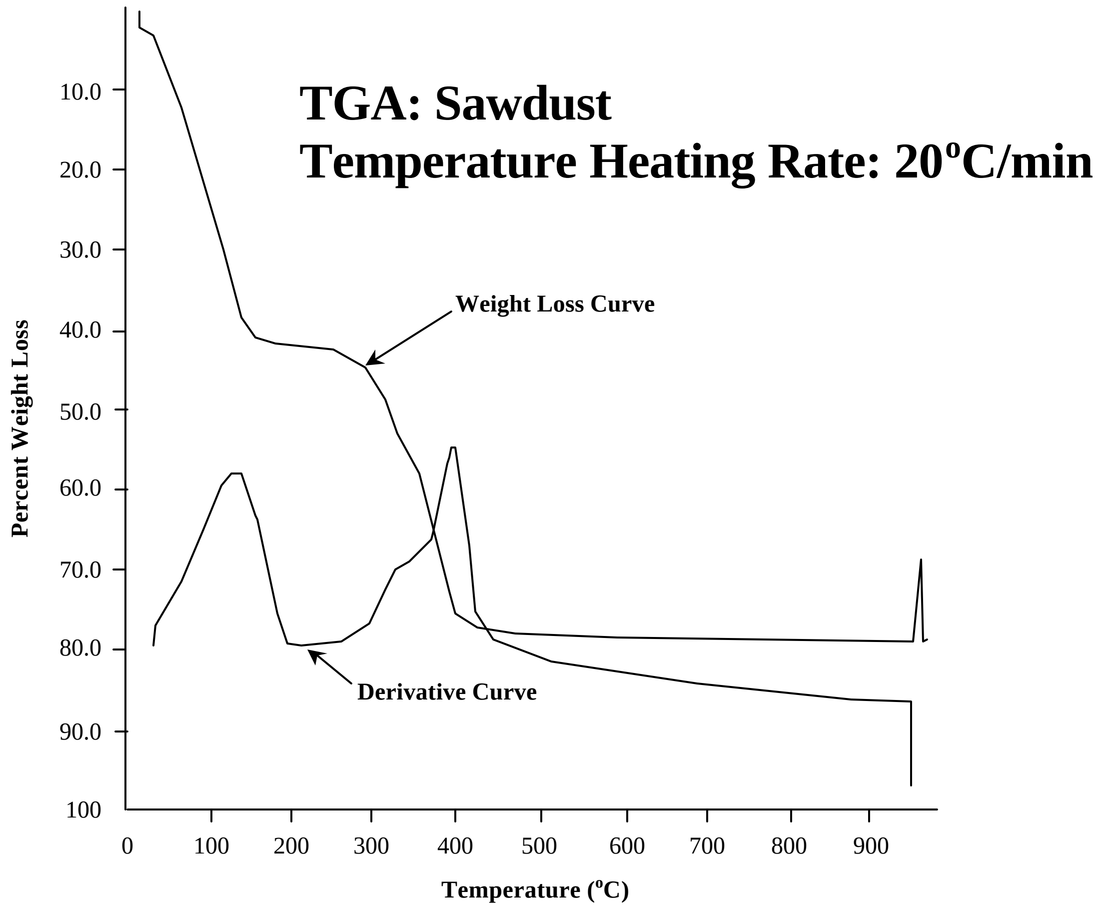

Figure 5. Thermogravimetric Analysis of Sawdust

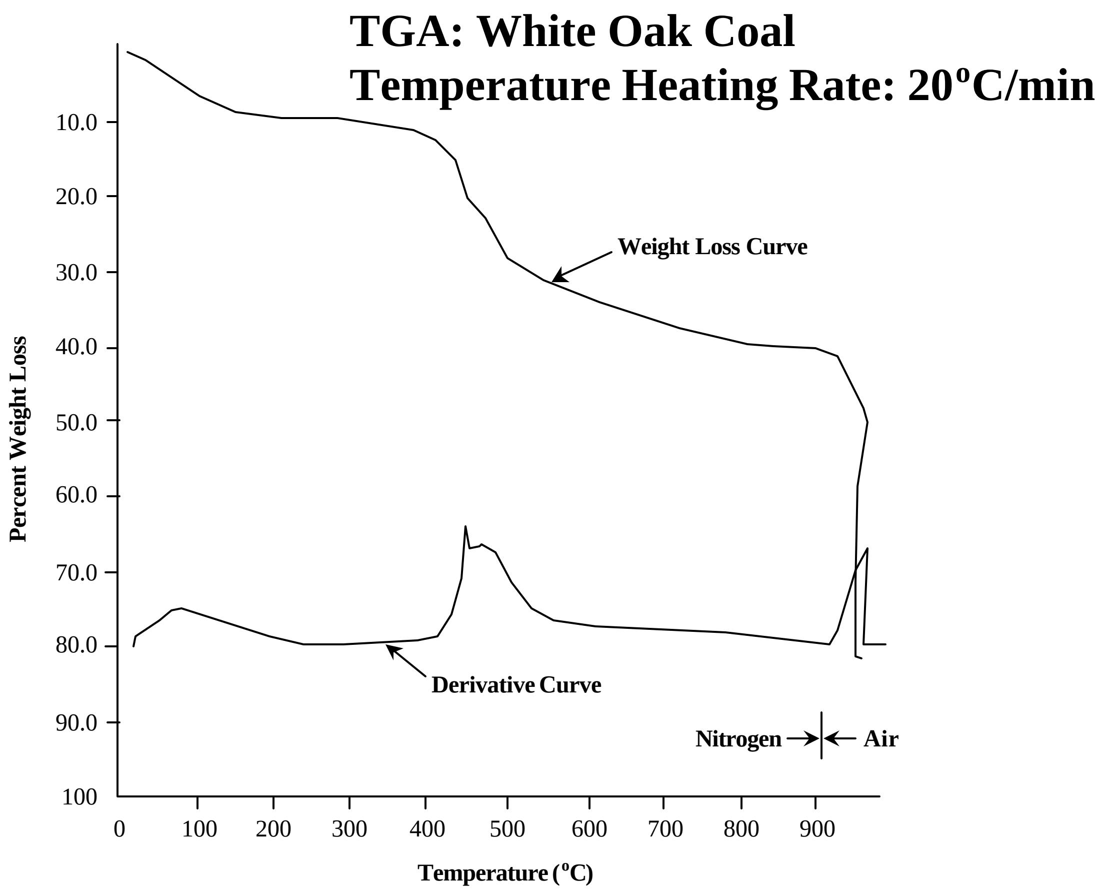

Figure 6. Thermogravimetric Analysis of White Oak Coal

5.0. COFIRING AND THE COMBUSTION PROCESS

The combustion consequences of cofiring with respect to the biomass fuel composition—particularly the fuel volatility—involve changing the process of combustion within any device. The introduction of biomass into a coal-fired PC or cyclone boiler adds a fuel where volatilization and gas-phase combustion is the dominant reaction sequence, rather than char formation and gas-solids oxidation as is the dominant combustion process for coal. This process of volatile release can be enhanced by using smaller particles, either of sawdust or of more finely divided switchgrass and herbaceous materials.

5.1. Cofiring and Combustion in Cyclone Boilers

The volatility causing early release of a significant quantity of volatiles in the cyclone barrel promotes early ignition of the mass of fuel in the barrel. This is particularly true of sawdust or other biomass is sized to 6.35 mm x 0 mm (¼” x 0”) is used as the fuel. If the wood waste or other biofuel is sized to <13 mm (<½”), the release of volatiles will be significant, but somewhat slower than the release from sawdust. If the biomass is sized to <19.05 mm (<¾”) the volatility will be significantly dampened, but still a major force in the combustion process. For biomass particles larger than 19 mm, the volatility impact is no longer a factor.

When the biofuels are sized to <6.35 mm or <12.7 mm, the biomass ignites rapidly and supports more early ignition of the entire mass of fuel in the cyclone. This has the effect of increasing the overall rate of combustion in the cyclone, and increasing the degree of completeness of combustion within the cyclone. It reduces the extent to which unburned fuel particles—or unburned carbon monoxide (CO) exits the reentrant throat of the cyclone and burns in the primary furnace. Visual evidence of this phenomenon has been developed at the Allen Fossil Plant using in-furnace video photography to compare combustion results when firing a blend of sawdust and coal with the results when firing only coal (Tillman et. al., 1996). There are significant temperature consequences associated with this combustion process.

It has long been speculated that the biomass reduces the temperature in the cyclone barrel. Modeling by Reaction Engineering International and optical pyrometry by Foster Wheeler demonstrates that this is not the case. The biomass burns with sufficient intensity that temperatures in the cyclone barrel are maintained (see Tillman, 1999). The Shafizadeh and DeGroot (1977) equation [1] documents the temperature function:

$$I_f = (dw/dt)h \qquad [1]$$

Where I_f is flame or reaction intensity, dw/dt is the weight loss with respect to time, measured by TGA, and h is the heat content of the fuel particle (cal/g). The rapid weight loss of the biofuels when compared to any coal compensates for the modest calorific value of biomass.

Temperatures in the primary furnace are reduced significantly when cofiring biomass with coal. This has been shown when firing wood waste with bituminous coal at the

Allen Fossil Plant (Tillman et. al., 1996), and when firing wood waste with a blend of PRB and western bituminous coal at the Michigan City Generating Station of NIPSCO (Tillman, et. a., 1998). The data at Allen Fossil Plant document a decrease in FEGT of about 40^{o}C (75^{o}F) when cofiring 15 percent sawdust with western coal or with Illinois Basin coal, given the boiler operating at full load; the data at Michigan City document an identical decrease in FEGT when cofiring 10 percent wood waste with a blend of PRB and western bituminous coal.

This early ignition—"sucking the fireball back into the cyclone"—mechanism is supported by the fuel volatility. The increased volatility of the biomass permits adjusting the primary-tertiary air/secondary air ratio from the traditional 15 percent/85 percent ratio towards a lower primary-tertiary air component. This further reduces the combustion in the primary furnace. Experiments at Allen Fossil Plant demonstrated that the PA-TA/SA ratio could be reduced to about 10 percent/90 percent, with significant combustion benefits, when firing high volatile sawdust with bituminous coal in a cyclone boiler.

The modified combustion process in cyclone boilers is responsible for the reductions in NOx emissions. Along with the reduced fuel nitrogen content of sawdust, the ability to reduce primary-tertiary air and the ability to complete more of the combustion in the cyclone barrel creates conditions favorable to the reduction of NO_x emissions from cyclone boilers. Reduction of other emissions such as fossil CO_2, SO_2, and trace metals results largely from substituting biofuels for coal, and fuels with low sulfur and low metals concentrations for fossil energy sources with higher sulfur and metals contents.

The ash characteristics of the biomass can contribute to the performance of the unit when sufficient biomass ash is added to the mix. Under such circumstances, the B/A ratio of the total fuel mix can be increased, reducing the T_{250} temperature and improving the viscosity of the slag formed in the cyclone. If wood wastes such as sawdust are fired, however, the contribution of the biomass ash to the total ash supply may be insufficient to significantly impact the B/A ratio.

5.2. Cofiring and Combustion in Pulverized Coal Boilers

Cofiring in wall-fired PC boilers, when the biomass is separately injected and when the biomass makes up ≥10 percent of the mass of fuel introduce into the boiler, can have a similar impact on the combustion process to the firing in a cyclone boiler. The biomass can be concentrated in a desired specific location within the flame of a burner—e.g., the center of the flame as is the case in the Seward design—for maximum impact. Under such circumstances, the volatiles in the biomass are concentrated and can be released immediately upon biofuel injection into the furnace. This release of the biomass volatiles can cause early ignition of the entire mass of fuel and can consume additional oxygen from the air supply. The consequence is increased fuel staging within the flame zone.

The biomass, if sized to <6 mm particles, will burn almost totally in the gas phase. The char oxidation reactions will be minimized. With furnace gas residence times normally designed into coal-fired boilers, near-complete burnout of the biomass particles can be assured. Note that if <6 mm is the top size of a fuel specification for biomass, typically at least 95 percent of the material will have a particle size of <3 mm (<1/8 in). Even with green sawdust, the concentration of sparklers or "fireflies" in the gaseous combustion products exiting the boiler at Seward Generating Station were minimal (Tillman and Battista, 1999). Similar results were experienced by the researchers at Blount St. Station when firing switchgrass.

The impact of cofiring on the combustion process in a tangentially-fired (T-fired) PC is heavily influenced by two factors: 1) the furnace operates as a single burner with multiple fuel injection points, and 2) the biomass is typically concentrated into 2 or 4 injection points among numbers ranging from 12 (a single furnace T-fired boiler with 3 rows of coal injectors) to 56 (a twin furnace T-fired boiler with 7 rows of coal injectors such as the Ottumwa Generating Station boiler). Selection of the injection locations, the percentage of cofiring, the injector design, and the particle size will all influence the ability of T-fired boilers to capitalize upon the volatility of the biomass as a means to reduce NO_x emissions.

The alkali in the biomass may be released in PC firing, and may react with sulfur in a complex series of reactions (Baxter et. al., 1996). In the highly alkaline, high ash herbaceous materials such as switchgrass or straw, the consequence can be a series of potassium or sodium reactions with chlorine in the fuel, followed by substitution of sulfur (from the coal) for chlorine in the alkali-chlorine deposits. Under select conditions, the consequence can be potassium sulfate or analogous compounds in the slagging and fouling deposits within the boiler.

There is some evidence that the ash from herbaceous biomass, in cofiring situations can deactivate Selective Catalytic Reduction (SCR) catalysts (see Wieck-Hansen, 1999). It is not clear at this time what concentrations of biomass are required to achieve this negative impact of cofiring, and it is also not clear whether this phenomena can be attributed selectively to straws and related herbaceous materials, or whether it will occur with all herbaceous materials. More research is underway in this area, and more research is needed in this area, to define the specific mechanisms involved and to determine the biomass fuels and the cofiring levels that cause this phenomenon.

In the cofiring of biomass with coal, the inorganic material or ash from the biomass is intermingled with the ash from the coal. In PC firing, 80 percent of the ash reports as flyash, and such commingling currently causes a definitional problem with respect to the sale of flyash as a pozzolan material for the cement industry. The ASTM committee responsible for Standard C-618 is addressing this problem. To date, however, this problem has not been resolved.

6. CONCLUSIONS

Cofiring has moved from engineering studies to parametric tests and now to long-term demonstrations. The demonstrations are addressing not only the issues of efficiency and NO_x emissions management, but also issues of fuel supply and logistics, fuel handling considerations, and related operational considerations. These demonstrations proceed despite the fact that biomass cofiring has caused a loss of boiler efficiency in virtually all tests and demonstrations. The environmental benefits of reduced NO_x, SO_2, fossil CO_2, and trace metal emissions such as mercury emissions is making this technology a favored approach to employing biomass as a renewable energy source in electricity generating stations.

In the process of demonstrating cofiring, specific combustion mechanisms have been documented based upon the fact that the biomass fuels are highly volatile and typically promote more gas-phase combustion than gas-solids oxidation. These mechanisms are responsible for much of the success of cofiring in reducing NO_x emissions at cyclone and PC boilers. The influence of volatility alone is shown in Figure 7, the influence of volatile/fixed carbon ratio on NO_x emissions during all of the testing at the Allen Fossil Plant of TVA.

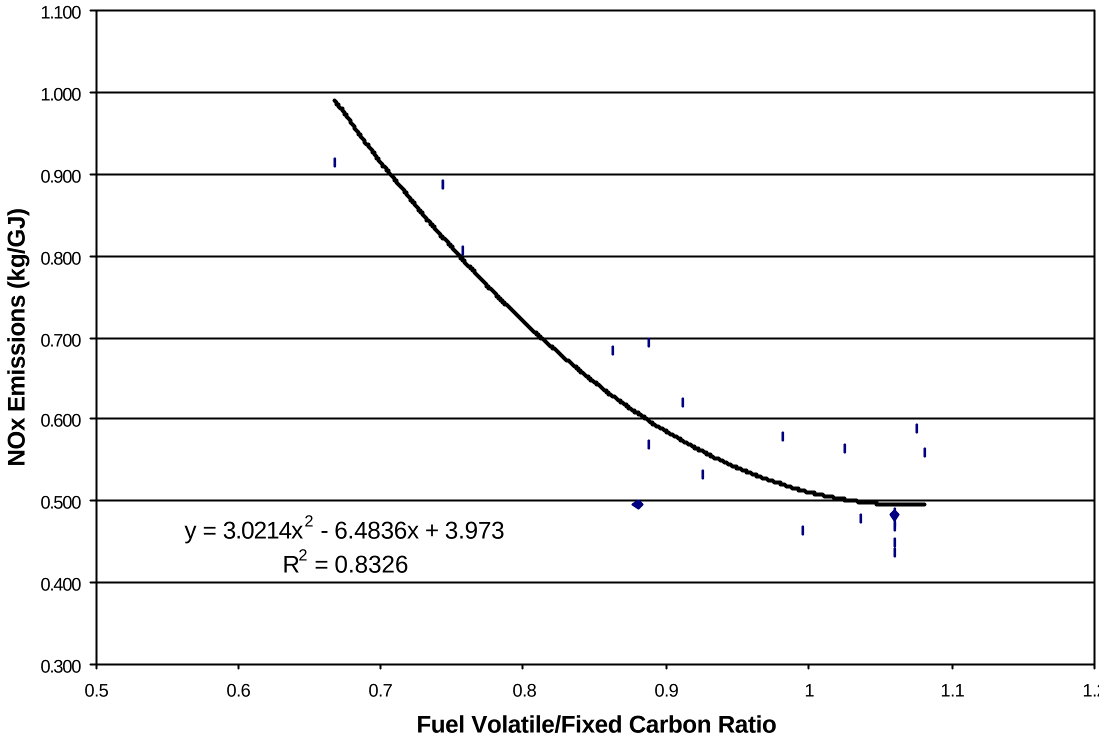

Figure 7. The Influence of Volatility on NO_x Emissions at the Allen Fossil Plant (Source: Tillman et. al., 1996)

Note, with respect to Figure 7, that there is a steep slope to the influence of fuel volatility, until the V/FC ratio approaches unity. At that point the curve begins to flatten, indicating that there is a V/FC ratio beyond which additional cofiring is not beneficial. Note, also, that the V/FC ratio reflects influences on causing early combustion, completing the combustion process in the cyclone barrel, and reducing FEGT. Clearly the influence of volatility is multi-faceted in cyclone boilers. Similar curves that virtually parallel the Allen curve can be drawn for PC boilers (Tillman et. al., 1996). The influence of volatility, again, is steep until the V/FC ratio approaches 1.0. At that point it flattens out. Again the influence is creating early ignition and the ability to cause internal staging of combustion in the flame.

The influence of cofiring on NO_x emissions from a range of tests in both cyclone and PC boilers is shown in Figure 8. This figure highlights the fact that the volatility of the fuel impacts the combustion process in both cyclone and PC boilers. The mechanism that appears to operate for PC boilers is similar to that for cyclone boilers. The biomass volatiles evolve rapidly, promoting ignition of the fuel mass. At the same time they scavenge available oxygen during initial volatile evolution, reducing the amount of oxygen available to form NO.

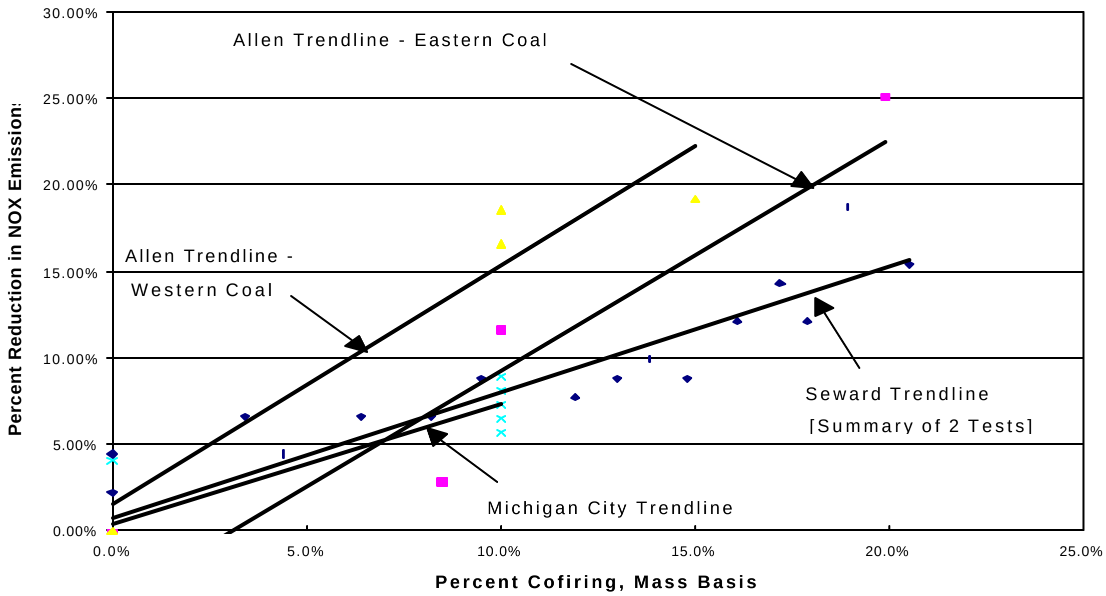

Figure 8. NO_x Emissions from a Series of Cofiring Tests and Demonstrations

Note the similarity of the slopes of these trend lines from various tests and demonstrations. Note, also, that testing at Bailly Generating Station extended the knowledge of cofiring and its influence on NO_x emissions.

The efficiency reductions, measured over five parametric tests at both the Allen Fossil Plant of TVA, the Michigan City Generating Station of NIPSCO, and the Seward Generating Station of GPU Genco (now Sithe Energies), can be summarized by the following equation (Tillman, Hughes, and Plasynski, 1999):

$$EL = 0.0044*B^2 + 0.0055*B \qquad [2]$$

Where EL is efficiency loss on a percentage basis and B is the percentage of biomass in the fuel blend measured on a mass basis. The r^2 for this equation is 0.70, indicating that the biomass is a dominant influence; at the same time other factors such as coal quality and firing conditions (e.g., excess air, air heater exit temperature) also substantially impacted the results. The NO_x emissions reductions, for all major tests, expressed on a percentage basis, were combined to yield the following approximation equation (Tillman, Hughes, and Plasynski, 1999):

$$RNO_x = 0.75*B \quad [3]$$

Where RNO_x is the percentage reduction in NO_x emissions, measured in kg/GJ or lb/10^6 Btu. The r^2 for equation [3] is 0.78. Another form of this NO_x reduction equation is:

$$RNO_x = 0.0008*C^2 + 0.0006*C + 0.075 \quad [4]$$

Where C is the percentage biomass cofiring on a calorific or Btu basis. The r^2 for equation [4] is 0.72. The NO_x benefit is disproportional to the fuel input on a calorific basis, up to some maximum biomass input.

Successes in reducing fossil CO_2 emissions, SO_2 emissions, and trace metal emissions result largely from the substitution of a renewable fuel for coal(*), substitution of a sulfur-deficient fuel for coal, and use of a fuel with low trace metal content.

A long term issue that merits consideration is the expansion of the biomass energy supply to include treated materials such as utility poles and crossarms, and railroad ties. Testing at NETL has provided results that are favorable to the use of such materials. Tests conducted by Kansas City Power & Light at the La Cygne Generating Station firing railroad ties in a cyclone boiler also provide favorable results. Other utilities have conducted short tests with railroad ties as well, and several industrial spreader-stoker boilers use these for fuel. The fundamental chemistry issues associated with the structural characteristics and volatility of such fuels merits analysis in order to understand the combustion processes associated with their cofiring.

Cofiring, then, is the low cost-low risk approach for utilities to use biomass in electricity generating applications. Successful testing has led to successful demonstrations. In an era of uncertainty caused by deregulation of generating stations and uncertainty in environmental regulation, it is emerging as a technology family of potential utility for numerous generating stations.

(*)**Note**: cofiring of biomass residues, rather than crops grown for energy, brings additional greenhouse gas mitigation. One ton CH_4 is equivalent to 11 tons CO_2 in terms of global warming impact. Cofiring biomass residues removes these materials from landfills. Given that a ton of biomass is ~35% C, then a ton of biomass interred in a landfill contains 700 lb C. About α of the C in organic matter interred in landfills reacts to form CH_4. Consequently 1 ton biomass yields about 230 lb C in the form of CH_4. This is $\cong$ 300 lb CH_4/ton biomass landfilled. The 300 lb CH_4 is about equal to 3300 lb fossil CO_2, or 1.65 ton fossil CO_2 equivalent. When 1 ton biomass residue, cofired in a coal-fired boiler, reduces fossil CO_2 emissions directly by 1 ton CO_2, it reduces the equivalent of 2.65 ton fossil CO_2 by also reducing methane formation from landfills. [see Hughes, E. 1998. Role of Renewables in Greenhouse Gas Reduction. Electric Power Research Institute, Palo Alto, CA. Report: TR111883]. Alternatively, the USEPA methodology yields a fossil CO_2 emissions (equivalent) reduction of 3.15 ton/ton of biomass burned.

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