PENNSTATE

Feasibility Analysis for Installing a Circulating Fluidized Bed Boiler for Cofiring Multiple Biofuels and Other Wastes with Coal at Penn State University

Ninth Quarterly Technical Progress Report for the Period 06/15/2002 to 09/14/2002

By

Bruce G. Miller and Sharon Falcone Miller
The Energy Institute;

Robert Cooper, Douglas Donovan, John Gaudlip,
Matthew Lapinsky, and William Serencsits
Office of Physical Plant; and

Neil Raskin and Tom Steitz
Foster Wheeler Energy Services, Inc.

October 14, 2002

Work Performed Under Grant No. DE-FG26-00NT40809

For
U.S. Department of Energy
National Energy Technology Laboratory
P.O. Box 10940
Pittsburgh, Pennsylvania 15236

By
The Energy Institute
The Pennsylvania State University
C211 Coal Utilization Laboratory
University Park, Pennsylvania 16802

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DISCLAIMER

EXECUTIVE SUMMARY

The Pennsylvania State University, under contract to the U.S. Department of Energy, National Energy Technology Laboratory is performing a feasibility analysis on installing a state-of-the-art circulating fluidized bed boiler and ceramic filter emission control device at Penn State's University Park campus for cofiring multiple biofuels and other wastes with coal, and developing a test program to evaluate cofiring multiple biofuels and coal-based feedstocks.

The objective of the project is being accomplished using a team that includes personnel from Penn State's Energy Institute, Office of Physical Plant, and College of Agricultural Sciences; Foster Wheeler Energy Services, Inc.; Parsons Energy and Chemicals Group, Inc.; and Cofiring Alternatives.

During this reporting period, the final technical design and cost estimate were submitted to Penn State by Foster Wheeler. In addition, Penn State initiated the internal site selection process to finalize the site for the boiler plant.

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1.0 Introduction

The Pennsylvania State University, under contract to the U.S. Department of Energy (DOE), National Energy Technology Laboratory (NETL) is performing a feasibility analysis on installing a state-of-the-art circulating fluidized bed (CFB) boiler and ceramic filter emission control device at Penn State's University Park campus for cofiring multiple biofuels and other wastes with coal, and developing a test program to evaluate cofiring multiple biofuels and coal-based feedstocks. Penn State currently operates an aging stoker-fired steam plant at its University Park campus and has spent considerable resources over the last ten to fifteen years investigating boiler replacements and performing life extension studies. This effort, in combination with a variety of agricultural and other wastes generated at the agricultural-based university and the surrounding rural community, has led Penn State to assemble a team of fluidized bed and cofiring experts to assess the feasibility of installing a CFB boiler for cofiring biomass and other wastes along with coal-based fuels.

The objective of the project is being accomplished using a team that includes personnel from Penn State's Energy Institute, Office of Physical Plant, and College of Agricultural Sciences; Foster Wheeler Energy Services, Inc.; Parsons Energy and Chemicals Group, Inc.; and Cofiring Alternatives.

The CFB boiler system that is being considered in the feasibility analysis is unique in that it:

1) is of compact versus traditional design;
2) includes modules to evaluate ceramic filters, along with fabric filters, for particulate matter control (recent work at Penn State has shown that ceramic filters have potential advantages regarding fine particulate matter and trace elements, i.e., mercury removal);
3) contains an advanced instrumentation package including temperature and pressure sensors, deposition and slagging probes, heat flux meters, and corrosion/erosion panels;
4) contains multi-fuel capabilities (making it a versatile test site for industry and government studies); and
5) is a commercial facility in a rural, agricultural setting that contains an engineering and agricultural-based university.

The state-of-the-art CFB boiler and ceramic filter device will allow the University to do the following:

- more economically supply heat to the University Park Campus;
- reduce the amount of airborne pollutants (i.e., NO_x, SO_2, particulate matter, and potentially trace elements), thus helping to reduce the overall emissions from the University's central heating plant;
- reduce the amount of agricultural and other waste products produced by the University that must be landfilled of land applied;
- reduce the amount of CO_2 (a greenhouse gas) emissions (by combusting waste biofuels); and

- ultimately serve as a large-scale (commercial demonstration size) test facility for federally- and other outside source-funded research and development projects related to cofiring of biofuels with coal and other coal refuse.

The feasibility analysis assesses: the economics of producing steam; the economics of off-sets such as utilizing multiple biomass and other wastes (i.e., sewage sludge); the value of a unique CFB test facility to perform research for industry, such as Foster Wheeler, and government agencies, such as the DOE; the environmental aspects of the CFB boiler; and the availability of funding from multiple sources including University, state, and federal sources. The feasibility study will also include developing a multiple-year program to test biofuels as the boiler system will be unique in that it will be heavily instrumented and will be able to handle multiple fuels.

1.1 Penn State's Steam Plants

Penn State University, Office of Physical Plant (OPP) currently operates a coal-fired central steam plant at the University Park Campus. The installed coal-fired capacity is 450,000 lb/h (pph) steam generated by four vibra-grate stoker boilers at 250 psig/540°F, which are used as baseload units. Additional steam generating capacity is available with gas or oil fire in three other boilers, totaling 260,000 pph. Electricity is also produced, as a by-product, with a maximum installed generating capacity of 6,500 kW. Currently at peak operation, which occurs when classes are in session and winter conditions experienced, 420,000 pph of steam are required. Steam requirements during the summer are 125,000 pph while approximately 200,000 pph of steam is required during the spring/fall.

Although the present total steam generating capacity is 710,000 pph, the University prefers not to operate the gas- and oil-fired boilers because the price of the natural gas and fuel oil is significantly higher than that of the coal. Ideally, the University would like to fire only coal and have sufficient coal firing capability to allow for one coal-fired boiler to be down without impacting steam production or forcing the operation of a gas/oil-fired boiler.

The four stoker-fired boilers at Penn State are all between 33 and 40 years old. When the units were installed (1961 to 1968), the projected life of a typical unit was expected to be approximately 40 years. Since that time, the life of the steam generating units has been reevaluated based on changing technology, economic, and regulatory factors. Life extension studies on many plants have now indicated that economic lives up to 50 to 60 years may be possible depending on the levels of maintenance, type of operation of the units, the cost of competing units, and other parameters related to these factors. Despite this, the University is exploring the possibility of installing a CFB boiler to cofire biomass and other waste streams with coal because of the following benefits:

1) Waste stream utilization. The CFB boiler would be multi-fuel capable with coal being the primary fuel and supplemented with waste streams. Waste stream disposal costs would be eliminated. For example, sewage sludge is currently landfilled at a cost of $47/ton.
2) Lower overall fuel costs. This includes using a lower grade coal including bituminous coal refuse (i.e., gob), growing grasses or crops on University land and cofiring in the boiler, accepting biomass and other wastes from the municipality, and being a test site for industry (e.g., Foster Wheeler) to conduct various fuel tests where the test fuel would be used in place of fuels purchased by the University.
3) Higher efficiency boilers.
4) Lower boiler emissions.
5) Possible alternative to spreading manure on fields and the associated odor problem.
6) Potential external funding source for a boiler replacement project. A recent energy assessment for Penn State showed that a coal-fired cogeneration plant was not economically feasible. However, OPP is reconsidering a boiler replacement because there is the possibility that some of the funding may come from other sources, e.g., industrial sponsorship, state and federal agencies.
7) Research component. By being a test site for industry (e.g., Foster Wheeler), not only would there be a decrease in fuel costs but there is the possibility that other operating costs such as labor could be reduced when industry-funded testing occurs.

Penn State's seven boilers are housed at two locations on campus as shown in Figure 1. The four coal-fired boilers and one small natural gas and oil-fired boiler are located at the West Campus Steam Plant (WCSP). There is not any room for installing additional boilers at this location. Two 100,000 pph of steam boilers, designed for natural gas and No. 2 fuel oil, are located at the East Campus Steam Plant (ECSP). This facility is used for peaking purposes. This location has been identified for future boiler expansion. At this time, OPP is interested in installing a CFB boiler with 200,000 pph of steam capacity at the ECSP. This size of a boiler could be installed without extensive upgrades to the current steam, water, and condensate return infrastructure. Final selection of the boiler size will be determined as part of the feasibility study.

1.2 Project Outline

The work consists of gathering design-related information, collecting and analyzing representative biofuels, coal, and coal refuse samples, developing a conceptual CFB boiler system design, developing a preliminary multiyear test program and associated budget, determining the system design/test program economics, and performing the feasibility study. The work is being performed via the following tasks:

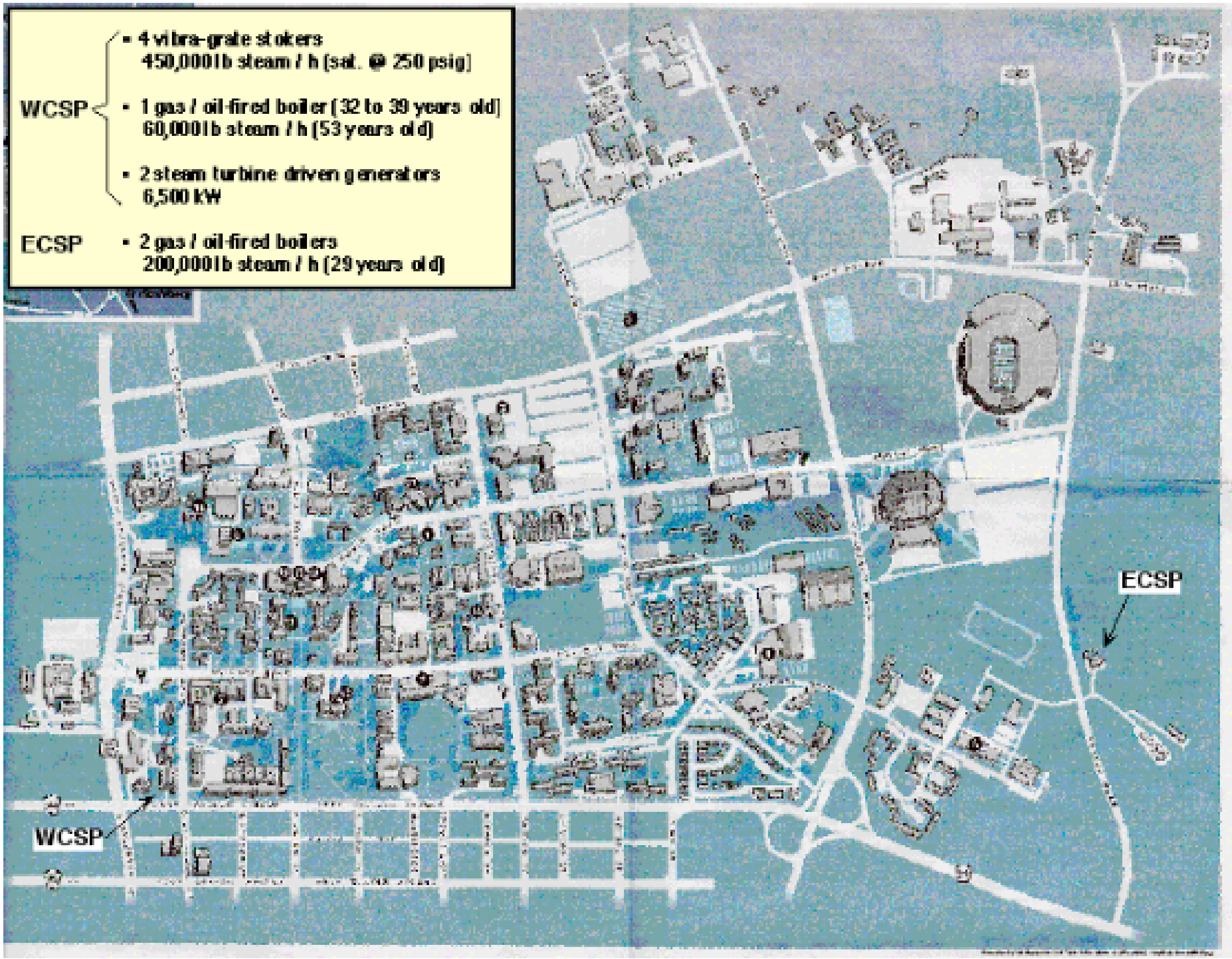

Figure 1. PENN STATE'S WEST CAMPUS AND EAST CAMPUS STEAM PLANTS

- Task 1. Information and Sample Collection
- Task 2. Biofuels and Biofuel/Coal Characterization
- Task 3. Develop Conceptual Design
- Task 4. Develop Preliminary Test Program/Budget
- Task 5. Determine System/Program Economics
- Task 6. Complete Feasibility Study
- Task 7. Project Management/Reporting

A summary of the activities being performed in each task includes:

Task 1. *Information and Sample Collection*: System requirements and infrastructure information will be assembled by Penn State and provided to Foster Wheeler. In addition, representative samples of biofuel and coal will be collected by Penn State.

Task 2. *Characterize Biofuels and Biofuel/Coal Combinations*: Penn State will characterize the samples collected in Task 1 and Foster Wheeler will use the analyses for assessing issues such as materials handling, deposition, and emissions.

Task 3. *Develop Conceptual Design*: A CFB boiler system will be designed to address the multiple project objectives. Foster Wheeler will perform the conceptual design with input from Penn State and Cofiring Alternatives.

Task 4. *Develop Preliminary Test Program/Budget*: A multiyear test program will be designed and costed to use the state-of-the-art CFB boiler system for investigating a range of issues when cofiring multiple biofuels and possibly other waste materials. Penn State will develop the preliminary test program with consultation from Foster Wheeler and Cofiring Alternatives.

Task 5. *Determine System/Program Economics*: Capital and operating costs will be determined. In addition, the availability of funding for the system and test program will be assessed.

Task 6. *Complete Feasibility Study*: The feasibility study will be completed by incorporating the results from each of the tasks.

Task 7. *Project Management/Reporting*: The project will be managed and reported per DOE's contractual requirements. Reporting will include the quarterly program/project management and technical progress reports, and a final report.

The status of Tasks 1 through 7 is presented in Sections 2.0 through 8.0, respectively. Activities planned for the next quarterly period are listed in Section 9.0. References and acknowledgments are contained in Sections 10.0 and 11.0, respectively. The project schedule is given in Figure 2, with a description of the milestones contained in Table 1.

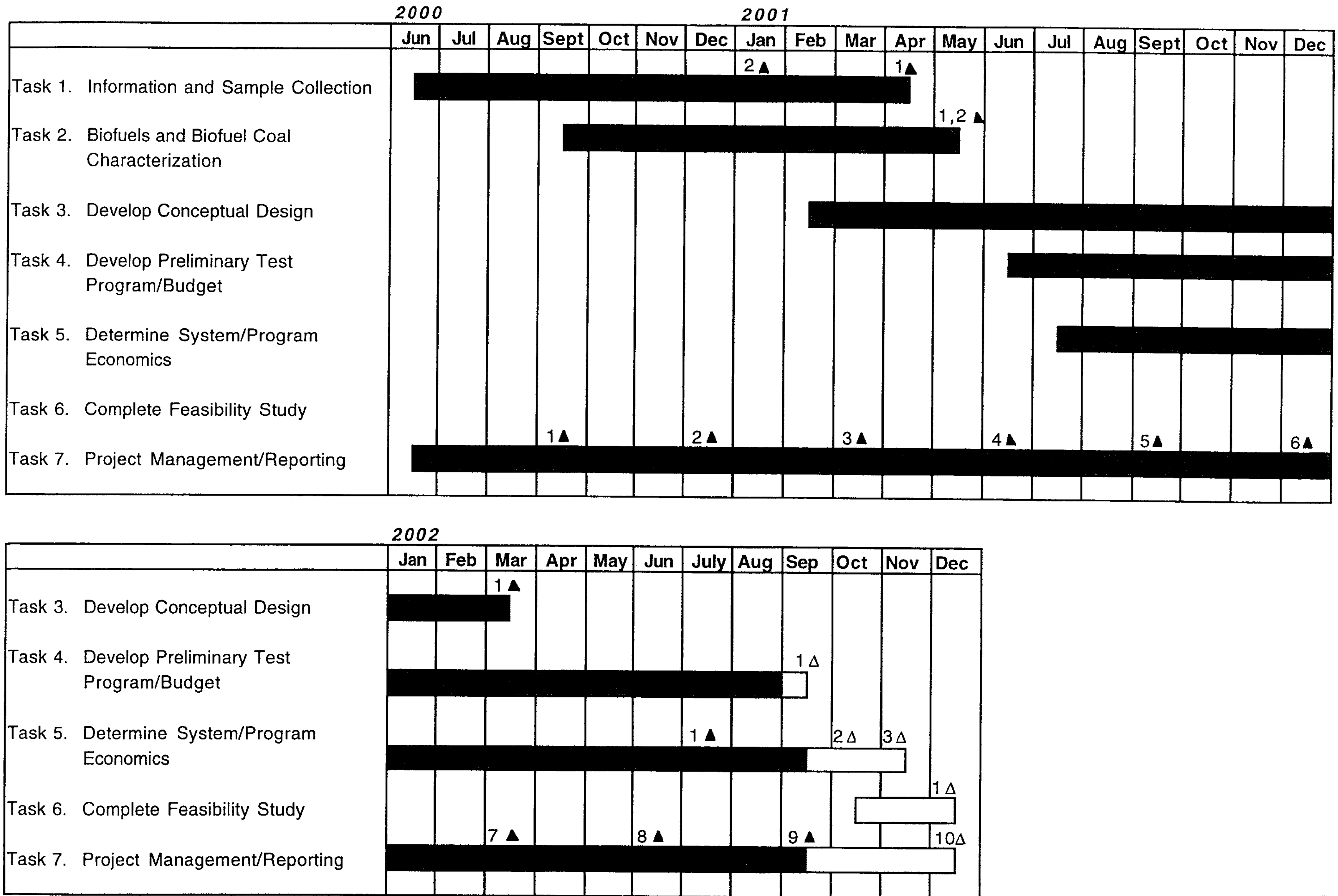

Figure 2. MILESTONE SCHEDULE

Table 1. Description of Milestones

Milestone	Description	Planned Completion Date	Actual Completion Date
Task 1, No. 1	Assemble system requirements and infrastructure information	04/15/01	04/15/01
Task 1, No. 2	Collect representative biofuel and coal samples	11/15/00	01/15/01
Task 2, No. 1	Complete characterization of biofuel samples	05/15/01	05/15/01
Task 2, No. 2	Complete characterization of biofuel/coal samples	05/15/01	05/15/01
Task 3, No. 1	Complete conceptual design	03/15/02	03/15/02
Task 4, No. 1	Develop preliminary task program/budget	09/15/02	
Task 5, No. 1	Determine capital cost	07/15/02	07/10/02
Task 5, No. 2	Determine operating costs	10/15/02	
Task 5, No. 3	Assess availability of funding	11/15/02	
Task 6, No. 1	Complete feasibility study	12/14/02	
Task 7, No. 1	Prepare program/project management and technical report 1	09/15/00	10/15/00
Task 7, No. 2	Prepare program/project management and technical report 2	12/15/00	12/15/00
Task 7, No. 3	Prepare program/project management and technical report 3	03/15/01	03/30/01
Task 7, No. 4	Prepare program/project management and technical report 4	06/15/01	07/13/01
Task 7, No. 5	Prepare program/project management and technical report 5	09/15/01	10/12/01
Task 7, No. 6	Prepare program/project management and technical report 6	12/15/01	01/18/02
Task 7, No. 7	Prepare program/project management and technical report 7	03/14/02	04/12/02
Task 7, No. 8	Prepare program/project management and technical report 8	06/14/02	07/12/02
Task 7, No. 9	Prepare program/project management and technical report 9	09/14/02	10/14/02
Task 7, No. 10	Prepare program/project management and technical report 10; prepare final report	12/14/02	

2.0 Task 1. Information and Sample Collection

Task 1 has been completed. System requirements and infrastructure information were assembled and provided to Foster Wheeler. This information is currently being used to develop the conceptual design. Representative samples of biofuels were collected by Penn State. Specifics on the samples collected were previously reported (Miller and Jawdy, 2000; Miller et al., 2000). Cofiring Alternatives completed a resource assessment of sawmills and secondary wood processors with wood wastes available for marketing as well as other potential biomass feedstocks for the CFB (Miller et al., 2000; Miller et al., 2001a)

3.0 Task 2. Biofuels and Biofuel/Coal Characterization

Task 2 has been completed. The biofuel analyses, contained in previous quarterly reports (Miller et al., 2000; Miller et al., 2001a), consisted of:

1) Proximate analysis;
2) Ultimate analysis;
3) Higher heating value;
4) Bulk density (where appropriate);
5) Chlorine content (where appropriate); and
6) Rheological characteristics (where appropriate).

In addition, the bulk chemical analysis of the biofuel ashes, stoker bottom and fly ash, and sewage sludge ash was determined. Chemical fractionation analysis was performed on the following samples to determine the mode of occurrence of major and minor elements:

1) Pine shavings;
2) Red oak shavings;
3) Dairy tie-stall manure;
4) Dairy free-stall manure;
5) Miscellaneous manure (mixture of various small-quantity manure streams that are collected at a central storage barn);
6) Sewage sludge;
7) Sheep manure;
8) Reed Canary grass;
9) Bottom ash; and
10) Fly ash.

The results from the spectrochemical and chemical fractionation analyses can be found in Miller et al. (2001b).

4.0 Task 3. Develop Conceptual Design

The conceptual design was completed by Foster Wheeler during the previous reporting period. Foster Wheeler submitted the design and cost package to Penn State during this reporting period. In addition, Foster Wheeler and Parsons formally presented the package to Penn State. Details of the design will be presented in the final report.

5.0 Task 4. Develop Preliminary Test Program/Budget

The budget for the test program is being finalized and will be completed during the next quarter.

6.0 Task 5. Determine System/Program Economics

Work in Task 5 continued during this reporting period. The cost estimate for the boiler islands and balance of plant was completed by Foster Wheeler and Parsons and submitted to Penn State. OPP is determining the costs to tie the new facility into Penn State's existing infrastructure (e.g., steam lines, condensate lines, etc.). In addition, operating costs are being determined.

7.0 Task 6. Complete Feasibility Study

Work continued on Task 6 during this reporting period. Foster Wheeler completed a report of the design and boiler island and balance of plant cost estimates. OPP has hired an architect to provide two renderings of the proposed boiler system – one from Beaver Stadium looking towards Mt. Nittany and one along Porter road. In addition, OPP is performing an internal site selection process to identify/justify the best site for the boiler system. The process includes identifying potential sites (15 were identified), preparing a list of selection criteria, and ranking the criteria to ultimately narrow the list down to one site. Through several 2-3 hour meetings, the list of potential sites was narrowed to three when the quarterly report was prepared.

8.0 Task 7. Project Management/Reporting

Technical reporting was performed per the contractual requirements. In addition, work continued on the final report.

One manuscript was prepared to be presented at the 2002 International Pittsburgh Coal Conference in Scottsdale, Arizona on June 24-27, 2002. The title and author of the manuscript are "A Feasibility Study for Cofiring Agricutural and Other Wastes with Coal at Penn State University," coauthored by Bruce G. Miller, Sharon Falcone Miller, Robert E.

Cooper, Neil Raskin, and Joseph J. Battista. A copy of the manuscript is contained in Appendix A.

9.0 Next Quarterly Activities

During the next reporting period, the project will be completed and the following will be done:

- The internal site assessment will be completed;
- The test plan budget will be prepared;
- The site renderings will be completed;
- The costs to tie the boiler system into the University's infrastructure will be determined;
- The project team will present the study to Upper Administration at Penn State; and
- The final report will be completed.

10.0 References

Miller, B.G. and C. Jawdy, "Feasibility Analysis for Installing a Circulating Fluidized Bed Boiler for Cofiring Multiple Biofuels and Other Wastes with Coal at Penn State University First Quarterly Technical Progress Report for the Period 06/15/2000 to 09/14/2000," Prepared for the U.S. Department of Energy National Energy Technology Laboratory, Pittsburgh, Pennsylvania, DE-FG26-00NT40809, October 9, 2000, 40 pages.

Miller, B.G., S. Falcone Miller, C. Jawdy, R. Cooper, D. Donovan, and J.J. Battista, "Feasibility Analysis for Installing a Circulating Fluidized Bed Boiler for Cofiring Multiple Biofuels and Other Wastes with Coal at Penn State University Second Quarterly Technical Progress Report for the Period 09/15/2000 to 12/14/2000," Prepared for the U.S. Department of Energy National Energy Technology Laboratory, Pittsburgh, Pennsylvania, DE-FG26-00NT40809, December 21, 2000, 95 pages.

Miller, B.G., S. Falcone Miller, R. Cooper, D. Donovan, J. Gaudlip, M. Lapinsky, W. Serencsits, N. Raskin, D. Lamke, and J.J. Battista, "Feasibility Analysis for Installing a Circulating Fluidized Bed Boiler for Cofiring Multiple Biofuels and Other Wastes with Coal at Penn State University Third Quarterly Technical Progress Report for the Period 12/15/2000 to 03/14/2001," Prepared for the U.S. Department of Energy National Energy Technology Laboratory, Pittsburgh, Pennsylvania, DE-FG26-00NT40809, March 30, 2001a, 72 pages.

Miller, B.G., S. Falcone Miller, R. Cooper, D. Donovan, J. Gaudlip, M. Lapinsky, W. Serencsits, N. Raskin, and D. Lamke, "Feasibility Analysis for Installing a Circulating Fluidized Bed Boiler for Cofiring Multiple Biofuels and Other Wastes with Coal at Penn State University Fourth Quarterly Technical Progress Report for the Period 03/15/2001 to 06/14/2001," Prepared for the U.S. Department of Energy National Energy Technology Laboratory, Pittsburgh, Pennsylvania, DE-FG26-00NT40809, July 13, 2001b, 22 pages.

11.0 Acknowledgements

Raymond Costello, from U. S. Department of Energy's Office of Energy Efficiency and Renewable Energy, is acknowledged for providing funding for the work under Grant No. DE-FG26-00NT40809. The project is being managed by the U.S. Department of Energy, National Energy Technology Laboratory and Philip Goldberg is the project manager. Randy Swope from Penn State's College of Agricultural Sciences Farm services and William Lamont from the Horticulture are Department are acknowledged for their assistance in quantifying and sampling various potential feedstocks.

APPENDIX A. MANUSCRIPT FOR THE 2002 INTERNATIONAL JOINT POWER GENERATION CONFERENCE

A Feasibility Study for Cofiring Agricultural and Other Wastes with Coal at Penn State University

by

Bruce G. Miller, Sharon Falcone Miller, Robert E. Cooper, Jr., Neil Raskin, and Joseph J. Battista

A Feasibility Study for Cofiring Agricultural and Other Wastes with Coal at Penn State University

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Nineteenth Annual International Pittsburgh Coal Conference

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ABSTRACT

The Pennsylvania State University, under contract to the U.S. Department of Energy, is performing a feasibility analysis on installing a state-of-the-art circulating fluidized bed boiler and ceramic filter emission control device at Penn State's University Park campus for cofiring multiple biofuels and other wastes with coal. The study is being performed using a team that includes personnel from Penn State's Energy Institute, Office of Physical Plant, and College of Agricultural Sciences; Foster Wheeler Energy Services, Inc., Foster Wheeler Energy Corporation; Parsons Energy and Chemicals Group, Inc.; and Cofiring Alternatives. A summary of the study, which includes the system design, biomass resource assessment, detailed fuel analysis, and agglomeration assessment, are discussed in this paper.

INTRODUCTION

The Pennsylvania State University, under contract to the U.S. Department of Energy (DOE), National Energy Technology Laboratory (NETL), is performing a feasibility analysis on installing a state-of-the-art circulating fluidized bed (CFB) boiler and ceramic filter emission control device at Penn State's University Park campus for cofiring multiple biofuels and other wastes with coal. In addition, as part of the study, a test program is being developed to evaluate cofiring multiple biofuels and coal-based feedstocks.

Penn State currently operates an aging stoker-fired steam plant at its University Park campus and has spent considerable resources over the last ten to fifteen years investigating boiler replacements and performing life extension studies. This effort, in combination with a variety of agricultural residues and other wastes generated at the agricultural-based university and the surrounding rural community, has led Penn State to assemble a team of fluidized bed and cofiring experts to assess the feasibility of installing a CFB boiler for cofiring biomass and other wastes along with coal-based fuels.

The objective of the project is being accomplished using a team that includes personnel from Penn State's Energy Institute, Office of Physical Plant, and College of Agricultural Sciences; Foster Wheeler Energy Services, Inc.; Foster Wheeler Energy Corporation; Parsons Energy and Chemicals Group, Inc.; and Cofiring Alternatives.

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- is of compact versus traditional design;
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- contains an advanced instrumentation package including temperature and pressure sensors, deposition and slagging probes, heat flux meters, and corrosion/erosion panels;
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The state-of-the-art CFB boiler and ceramic filter device being considered will allow the University to do the following:

- more economically supply heat to the University Park campus;
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- reduce the amount of agricultural residues and other waste products produced by the University that must be landfilled or land applied;
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- ultimately serve as a large-scale (commercial demonstration size) test facility for federally- and other externally-funded research and development projects related to cofiring of biofuels with coal and other coal refuse.

In the feasibility analysis, which will be completed by December 2002, the following items are being assessed: the economics of producing steam; the economics of off-sets such as utilizing multiple biomass feedstocks and other wastes (*i.e.*, sewage sludge); the value of a unique CFB test facility to perform research for industries, such as Foster Wheeler, and government agencies, such as the DOE; the environmental aspects of the CFB boiler; and the availability of funding from multiple sources including University, state, and federal sources. The feasibility study also includes the development of a multiple-year program to test biofuels as the boiler system will be unique in that it will be heavily instrumented and will be able to handle multiple fuels.

Activities that have been completed (as of June 2002) include: assembly of system and infrastructure requirements for the system design, a biomass resource assessment, collection and analysis of representative samples, assessment of materials handling, deposition, and emissions issues, the conceptual design, and determining the capital costs. Items in progress include finalizing a multiyear test program to use the CFB boiler system, determining operating costs, assessing availability of funding for the system and test program, and integrating the results into a feasibility study.

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- Potential external funding source for a boiler replacement project. A recent energy assessment conducted a few years ago for Penn State indicated that a coal-fired cogeneration plant was not economically feasible. However, OPP is reconsidering a boiler replacement because there is the possibility that some of the funding may come from other sources, *e.g.*, industrial sponsorship, state and federal agencies.
- Research component. By being a test site for industry (*e.g.*, Foster Wheeler), not only would there be a decrease in fuel costs but there is the possibility that other operating costs such as labor could be reduced when industry-funded testing occurs.

Penn State's seven boilers are housed at two locations on campus as shown in Figure 1. The four coal-fired boilers and one small natural gas and oil-fired boiler are located at the West Campus Steam Plant (WCSP). There is not any room for installing additional boilers at this location. Two 100,000 pph of steam boilers, designed for natural gas and No. 2 fuel oil, are located at the East Campus Steam Plant (ECSP). This facility is used for peaking purposes. This location has been identified for future boiler expansion. At this time, OPP is interested in installing several coal-fired boilers with 200,000 pph of steam capacity each at the ECSP. This is discussed in more detail later.

BIOMASS RESOURCE ASSESSMENT

An assessment of the types and quantities of potential feedstocks was performed. This included wastes and by-product streams at Penn State along with wood wastes from sawmills and secondary wood processors in the surrounding area (*i.e*., within 75 miles from University Park although the distance was limited to 45 miles when determining the final design firing rate). Approximately twenty different biomass, animal waste, and other wastes were identified, collected, and analyzed. These potential feedstocks include the following: animal wastes such as dairy tie-stall and free-stall manure (mixed with leaves and brush to make it stackable), beef manure, horse manure, poultry litter, sheep manure, and swine waste; wood waste and brush; pallets; Reed Canary grass grown on Penn State's wastewater treatment facility's effluent spray field; bottom and fly ash from the stokers; agricultural plastics including horticulture hard plastics and plastic bags, bale tarps, and silo bunker covers; used oil; tires; wood shavings and chips from the surrounding region; coal/paper pulp pellets from a nearby paper mill; and sewage sludge. Details of the resource assessments and results from analysis of all the feedstocks can be found elsewhere, while Table 1 summarizes the results [2-4].

The boiler, which is designed to produce 200,000 lb saturated steam (@250 psig)/h and is discussed in a following section, will have a thermal firing rate of 200 million Btu/h. The preliminary breakdown of the fuels for the boiler is illustrated in Table 2. The firing rate information was developed assuming that all the animal wastes, sewage sludge, and Reed Canary grass produced by the University will be utilized in the boiler. In addition, ≈27% of the total wood wastes from the region (≈475 tons/week used in the boiler out of ≈1,770 tons/week total produced) is being used in the preliminary design. The ratio of the biomass/wastes-to-total fuel is 0.21 based on thermal input and 0.47 based on quantity of fuel fired.

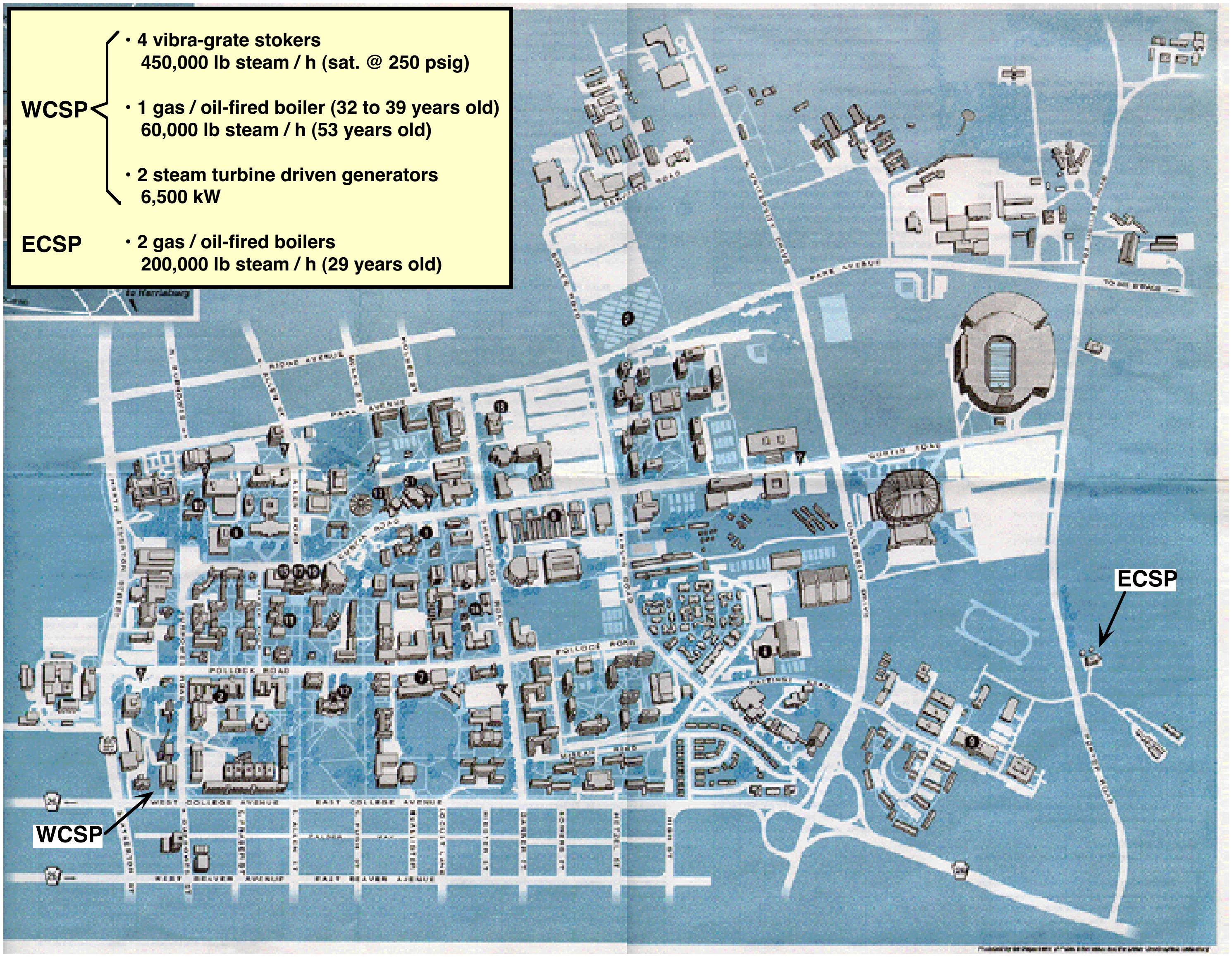

Figure 1. PENN STATE'S WEST CAMPUS AND EAST CAMPUS STEAM PLANT

Table 1. Potential CFB Feedstocks

Material	Quantity (tons/yr)
Biomass at University Park	
Animal Wastes:	
Dairy manure (tie stall and free stall mixed with leaves)	13,200
Manure from covered manure barn (poultry litter, horse barn, misc.)	1,180
Beef manure	1,033
Sheep manure	265
Swine waste (@ 2.2% solids)	2,505
Wood waste/brush	150
Pallets	92
Reed Canary grass	600
Other Wastes at University Park	
Sewage sludge (@ 2.2% solids)	2,708
Bottom ash	6,990
Fly ash	1,445
Agricultural Plastics - total	2.1
Horticulture hard plastics	0.2
Horticulture plastic bags	1
Bale tarps	0.5
Silo bunker covers	0.4
Used oil	14
Tires	5
Biomass from Surrounding Region (within 45 miles of University Park)	
Wood products (chips/shavings)	>90,000

Table 2. Design Firing Rate Information (based on a total firing rate of 200 million Btu/h)

Feedstock	Maximum Firing Rate (lb/h, as received)	Maximum Thermal Input (Btu/h)
Coal	16,667	158,284,634
Sewage Sludge	780	475,700
Swine Waste	715	116,777
Dairy Manure	3,800	10,600,000
Beef Manure	295	944,000
Sheep Manure	76	290,400
Covered Barn Manure	336	507,800
Reed Canary Grass	171	369,189
Plastics	0.6	11,500
Wood Chips/ Shavings	5,700	28,400,000

FUEL CHARACTERIZATION/ AGGLOMERATION ASSESSMENT

It has long been recognized that the mode of occurrence of inorganic elements in fossil fuels has a direct bearing on their behavior during combustion [5-8]. The occurrence of inorganic elements in biofuels is also important. Inorganic species are incorporated in biomass in several ways due to the chemical makeup of the biomass, its origin, and the manner in which it is collected for utilization as a fuel. The fuel may be of plant or animal base or a mixture of both due to farming practices (*i.e.,* mixture of manure and bedding). Inorganic species can occur as ion-exchangeable cations, as coordination complexes, and as discrete minerals. In the case of firing a single fuel, such as coal, it is possible to predict ash behavior to avoid system problems. However, it becomes more complex to predict ash behavior in the case of firing multiple fuels in proportions that vary with time, *e.g.,* seasonal changes, and are extremely heterogeneous.

Like low-rank coals, biomass materials often contain significant amounts of alkali metals, *e.g.,* potassium and sodium, and alkaline earth metals, *e.g.,* calcium and magnesium, which are rapidly released into the gas phase and interact with other elements resulting in problems with fouling, slagging and corrosion. In general, potassium and sodium that are associated with the organic structure of the fuel tend to be problematic in that they can contribute to the formation of inorganic phases that have lower melting points. Studies conducted on ash formation during coal combustion show that the incorporation of moderate amounts of alkalis and alkaline earth elements into silicates enhances the coalescence and agglomeration of inorganics due to formation of "sticky" molten phases [6,7,9,10]. The presence of low-melting point phases in a fluidized bed combustor (CFB) results in the formation of clinkers that can compromise the bed fluidity. It is also important to recognize that the blending of biomass feedstocks and coal does not necessarily result in simply an additive effect of problematic elements. Changes in the feed blend may or may not have devastating effects on system operation. Predicting these effects is based on an understanding of the manner in which the inorganics in fuels interact during combustion and their effect on the chemical and physical properties of the ash and gas phases in the system.

Chemical fractionation analysis was performed on eleven of the major feedstock streams to assess the potential for bed agglomeration. A detailed discussion of the biomass fuels characterized via chemical fractionation and their theoretical propensity to form liquid phases during combustion based on thermodynamic modeling is given elsewhere [11,12]. These calculations were performed using a series of fuel blends as input into a Gibbs free energy minimization program called FactSage developed at the Facility for the Analysis of Chemical Thermodynamics (FACT), Centre for Research in Computational Thermochemistry (CRCT), École Polytechnique de Montréal, Canada, and GTT Technologies [13]. The program calculates equilibrium composition for a given system at a set of defined temperature and/or pressure conditions.

The proximate, ultimate, and ash analyses of the coal and seven of the biomass fuels are given in Table 3 while a complete analysis of all fuels is provided elsewhere [3,4].

The chemical fractionation procedure is based on an element's varying solubility as a result of its occurrence in a fuel. A procedure used to fractionate low-rank coals at the University of North Dakota Energy and Environmental Research Center [Benson and Holm, 1985] and later modified by Baxter [1994] was further modified to better address handling issues particular to biomass fuels. A schematic representation of the method is shown in Figure 2 and discussed in detail elsewhere [12,14,15,16]. The chemical fractionation methodology was developed as a consequence of the extremely heterogeneous character, *i.e.,* grindability, density and wetability, of the various components that constitute a biofuel. The manner in which biofuels are acquired make it difficult to obtain representative samples or highly reproducible analytical results. This variability is compounded by seasonal variations in the character of biofuels. Therefore, fluctuations in biofuel composition can be expected.

Table 3. Proximate, Ultimate and Ash Analysis of Cofire Coal and Biomass Fuels

	Cofire Coal	Pine Shavings	Reed Canary Grass	Sheep Manure	Dairy Free-Stall Manure	Dairy Tie-Stall Manure	Misc. Manure	Poultry Litter
Moisture	5.0	45.0	65.2	47.8	70.3	69.8	50.5	20.0
Proximate analysis (wt.%, db)								
Volatile matter	24.16	84.7	76.1	65.2	30.6	30.1	21.8	55.3
Ash	14.70	0.1	4.1	20.9	62.3	62.5	73.5	17.0
Fixed carbon	61.14	15.2	19.8	14.0	7.1	7.4	4.8	7.7
Ultimate analysis (wt. %, db)								
Carbon	72.75	49.1	45.8	40.6	22.1	22.6	19.6	38.1
Hydrogen	3.91	6.4	6.1	5.1	2.9	2.9	2.5	5.6
Nitrogen	1.50	0.2	1.0	2.1	1.1	1.1	1.0	3.5
Sulfur	2.27	0.2	0.1	0.6	0.1	0.1	0.1	0.6
Oxygen	4.87	44.0	42.9	30.7	11.5	10.8	3.3	30.9
HHV (Btu/lb, db)	13,118	8,373	7,239	6,895	3,799	8,203	3,114	6,399
HHV (kJ/kg, db)	30,493	19,455	16,828	16,021	8,832	19,070	7,238	14,874
Bulk density (lb/ft^3)	--	11.9	3.12	23.1	50.5	50.5	43.7	--
Bulk density (g/cc)	--	0.10	0.05	0.37	0.81	0.40	0.7	--
Ash Analysis (wt.%)								
Al_2O_3	25.34	13.4	1.66	3.08	0.96	2.26	1.34	9.14
BaO	--	0.15	0.05	0.05	0.02	0.02	0.01	0.05
CaO	2.28	8.75	9.57	12.8	6.38	23.3	3.44	12.7
Fe_2O_3	18.34	5.94	1.47	1.95	1.29	1.37	0.93	4.04
K_2O	2.22	4.94	18.1	23.4	6.75	10.7	1.77	9.94
MgO	0.82	3.35	5.29	5.74	2.65	8.91	1.06	4.01
MnO	--	0.49	0.11	0.17	0.17	0.14	0.03	0.36
Na_2O	0.25	1.38	2.34	4.64	1.32	7.04	0.88	3.60
P_2O_5	0.4	1.44	13.8	9.21	2.90	14.7	2.54	14.0
SiO_2	48.2	57.2	43.0	29.3	74.98	26.0	84.82	39.4
SO_3	0.67	0.05	0.02	5.52	0.04	0.14	0.01	2.58
SrO	--	0.80	0.11	0.03	0.10	0.11	0.14	0.03
TiO_2	--	1.16	4.99	0.20	2.06	5.08	1.20	0.51

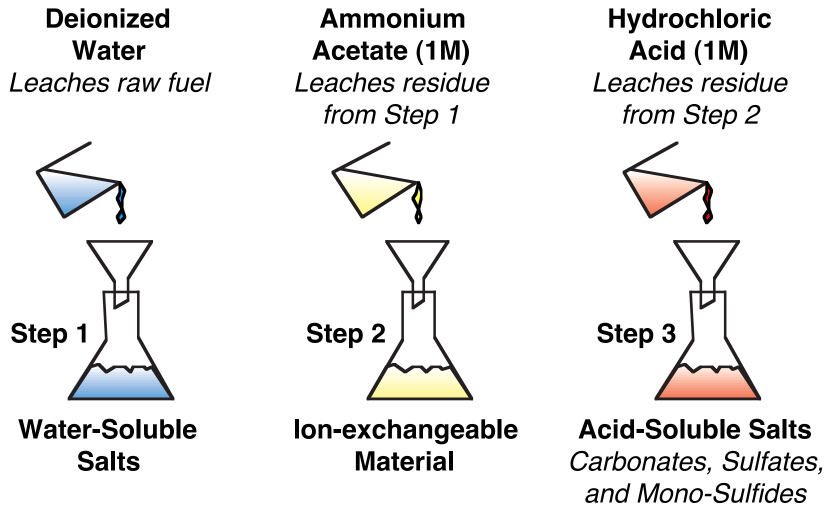

Figure 2. SHCEMATIC REPRESENTATION OF THE CHEMICAL FRACTIONATION METHOD

Each step in Figure 2 results in a liquid and solid residue sample, both of which were analyzed for the major and minor elements Al, Ba, Ca, Fe, K, Mn, Mg, Na, P, Si, Sr, S and Ti. The detailed results are given elsewhere [14,15]. Analysis of both residues was conducted to determine the occurrence of various elements in the biofuels. The water soluble and ion-exchangeable constituents of the fuels are indicative of species that are highly reactive during combustion, *i.e.*, organically-bound or water soluble mineral phases such as carbonates, that tend to lead to enhanced deposition and agglomeration. Potassium occurs predominately in water soluble/ion-exchangeable forms (≥95%) in all four manures and the Reed Canary grass. Sodium is also present predominately in water soluble/ion-exchangeable form (≥ 90%) with the remaining sodium present in an insoluble form. Calcium in the fuels is either present in a water soluble/ion-exchangeable form or acid soluble form with the remaining calcium in the insoluble portion of the fuel. Aluminum and silicon remain in the insoluble portion of the fuel. Silicon is attributed to the presence of straw and dirt from the floor of dairy and poultry barns.

A series of fuel blends were used as input into the FactSage program. The chemical fractionation results determined the input composition for each fuel blend. Insoluble elements such as silica are fairly inert at lower temperatures typical of a fluid bed, whereas the water soluble and ion-exchangeable elements are quite reactive.

Table 4 contains examples of blends that were evaluated. The FactSage results, listed in Table 5, demonstrate the impact that certain elements have on potential clinkering or fouling problems. The presence of a liquid phase in the poultry litter resulting in agglomeration was observed during pilot-scale FBC testing at Penn State and as illustrated in Figure 3 [17, 18]. The agglomeration was eliminated upon the addition of kaolin clay, which has the net effect of increasing the aluminum in the ash and shifting the equilibrium composition away from the formation of phases having lower melting points. In addition, the kaolin clay also dilutes the concentration of alkali earth elements. This effect is also observed in Table 5 where no liquid phases are present in the manure/coal cofire scenario.

Table 4. Percent Thermal Input of Proposed and Theoretical Fuel Blends Based on a Firing Rate of 58.6MW$_t$ (200 MMBtu/h)

% Thermal Input					
Fuel	**Baseline Blend**	**Chicken Litter**	**Manure Blend 1**	**Manure Blend 2**	**Manure-Coal Cofire**
Coal	83.8				84.9
Sewage Sludge	0.4				
Sheep Manure	0.1		59.0	25	3.9
Chicken Litter	0.0	100			
Dairy Tie-Stall Manure	0.4		21.5	25	4.0
Dairy Free-Stall Manure	0.0		8.1	25	3.4
Misc. Manure	0.3		11.7	25	3.9
Red Oak Shavings	8.4				
Pine Shavings	6.5				
Reed Canary Grass	0.2				

Table 5. Inorganic Phases Predicted at Equilibrium at 1,650°F. All Phases are Solid Unless Followed by *(l)* Indicating a Liquid Phase. Liquid Phases are also Indicated in Bold Typeface.

	Weight %				
Phase	Baseline Blend	Chicken Litter	Manure Blend 1	Manure Blend 2	Manure-Coal Cofire
SiO_2/tridymite	25.7		11.0	50.0	27.0
$CaAl_2Si_2O_8$/anorthite	19.4				18.7
Fe_2O_3/hematite	17.1		1.7	1.2	9.1
$Al_6Si_2O_{13}$/mullite	14.8				
$KAlSi_2O_6$/leucite	11.1	7.8	10.8	7.3	19.4
$Mg_2Al_4Si_5O_{18}$/cordierite	8.3				
$NaAlSi_3O_8$	2.7				11.8
$CaSO_4$/anhydrite	1.2				1.5
$Ca_3Fe_2Si_3O_{12}$/andradite		25.7			1.1
$MgOCa_2O_2Si_2O_4$/akermanite		13.9			
$Na_2Ca_2Si_3O_9$		29.4			
Mg_2SiO_4/forsterite		8.2			
$K_3Na(SO_4)_2$		7.0			
Na_2SO_4*(l)*		**3.1**			
$CaOMgOSiO_2$/monticellite		4.9			
$K_2Si_4O_9$*(l)*			**31.0**	**13.3**	
$Na_2Ca_3Si_6O_{16}$			22.2	13.2	
$MgOCaOSi_2O_4$/diopside			15.4	10.0	11.3
$Na_2Mg_2Si_6O_{15}$			8.4	3.3	
K_2SO_4			6.2	1.7	

The FactSage equilibrium calculations suggest that a cofire of biofuels with an appropriate nonfouling coal should not pose any problems in a CFB system given that the coal makes up a majority of the thermal input. FactSage consistently predicted $K_2Si_4O_9$ *(l)* to be present at 1,650°F with biofuels having low aluminum levels and significant concentration of alkali earth elements. Only 10% (normalized with respect to SiO_2 and Al_2O_3) of K_2O present in a system was enough to result in the formation of $K_2Si_4O_9$ *(l)* at equilibrium that could compromise a CFB system. Thermodynamically it appears that the baseline cofire blend being evaluated for the Penn State CFB boiler is feasible and that there is flexibility in the biofuel

Figure 3. EXAMPLE OF CLINKERS FORMED IN FLUIDIZED BED DURING POULTRY LITTER TESTING

blends that can be handled. This can be expanded to multifuel fluidized bed boilers in general in that they can be engineered to accommodate a wide range of manures/poultry litter.

SYSTEM DESIGN

Foster Wheeler's state-of-the-art Compact atmospheric circulating fluidized bed (ACFB) boiler (see Figure 4) is being used in the plant design and feasibility study. This technology is based upon Foster Wheeler's proven atmospheric circulating fluidized bed combustion process.

The key to the state-of-the-art ACFB boiler is its Compact separator, which is Foster Wheeler's state-of-the-art development to minimize plant capital and operating costs. The Compact separator is best described as a "square cyclone". The round refractory-lined plate cyclone of the traditional ACFB is replaced with a rectangular separator. The separator, which is joined to the furnace without expansion joints, is fabricated with flat walls constructed from conventional water-cooled membrane panels and covered with a thin refractory lining. Center gas inlet and gas outlets towards the sides impart a swirl to the gas and solids, allowing for solids separation just as in a cyclone. The Compact separator has now been proven in over 20 commercial applications worldwide and the units in operation have demonstrated very high availability since start up. The Compact separator provides:

- The same proven reliability and performance demonstrated by over 150 Foster Wheeler ACFB units worldwide;
- The same fuel flexibility: all coal grades, peat, wood waste, lignite, petroleum coke, sludges, bituminous gob, anthracite culm, tires, and bagasses; and

- The same clean-burning process resulting in air emissions which meet even the most stringent regulations in California.

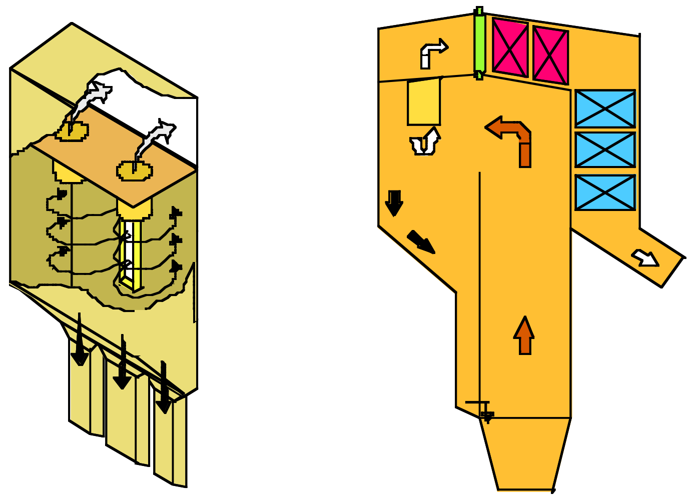

Figure 4. STATE-OF-THE-ART COMPACT ACFB BOILER

An overview of a typical compact CFB boiler plant is shown in Figure 5. Penn State's design, however, will contain three CFB boilers, each producing 200,000 lb steam/h as part of Penn State's proposed overall master boiler plant plan. No drawings of the Penn State system were available when this paper was being prepared (June 2002). The preferred site is being laid out to accommodate Units 2 and 3 five and ten years, respectively, after the installation of Unit 1. Unit 1 will be designed to produce high-temperature, high-pressure steam (*i.e.,* 950°F/950 psig) but will initially produce only saturated steam at 250 psig. When Unit 2 is constructed, a turbine will also be installed to produce electricity using steam from both units. Eventually all three units will be cogeneration facilities.

The initial Compact CFB boiler plant is being designed to receive, store, process and handle the base fuel, *i.e.,* coal, in addition to the limestone, fly ash, and bottom ash. Additionally, a simple biofuel feed train consisting of a "wood" storage silo with double outlet screw feeders has been designed for the sawdust and woodchips. The screw feeders dump the "wood" fuel onto either of the two coal conveyors. These conveyors direct the fuel mixture through rotary valves directly into the Compact CFB boiler combustion chamber.

Preliminary designs and cost estimates of additional biofuel feed systems are being prepared. Should the decision be made to proceed with the biomass testing, then the additional feed systems will be designed, purchased, constructed, and commissioned as a part of that specific test requiring a modification and/or addition to the existing biofuel feed systems.

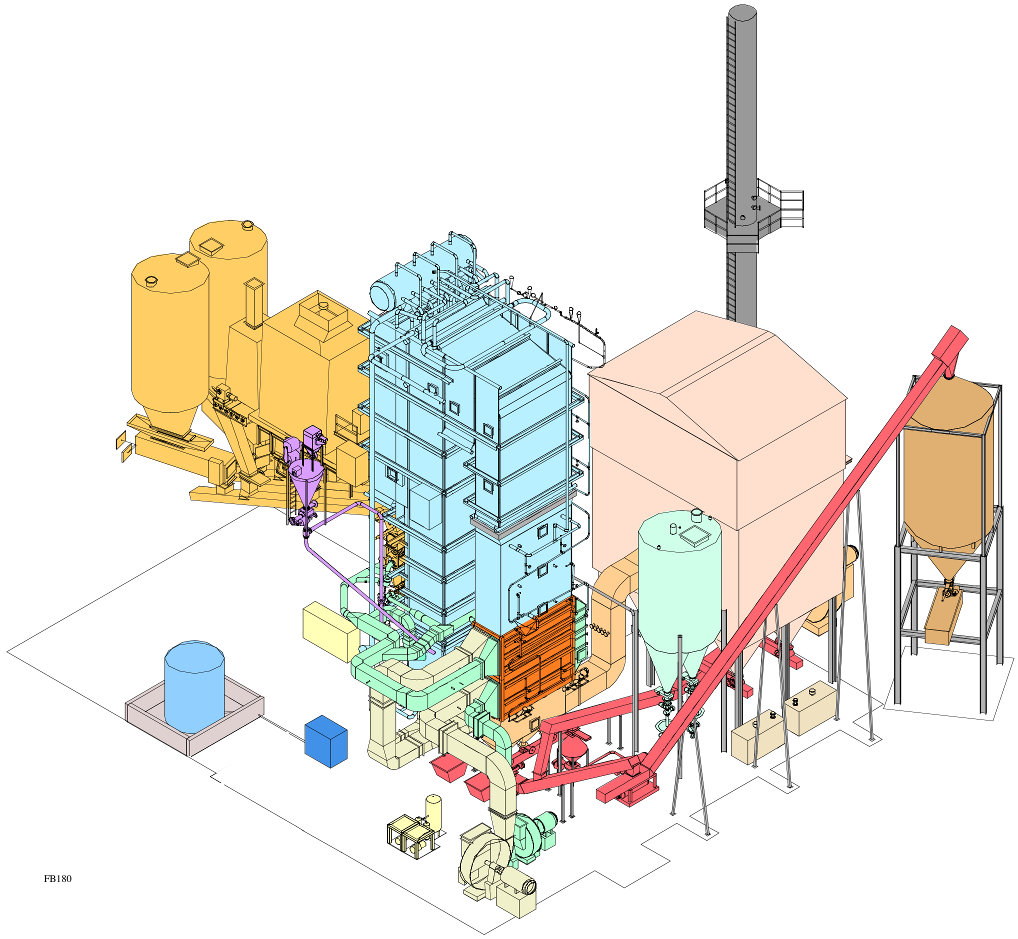

Figure 5. OVERVIEW OF A TYPICAL COMPACT CFB BOILER PLANT

The boiler has been designed to accommodate special materials for erosion and/or corrosion testing including test coupons, slagging and fouling probes, and heat flux meters. As mentioned previously, the unit has been designed and laid out to accommodate the addition of an emission reduction system prior to the baghouse. There are two stub duct sections designed into the existing unit's outlet ducting (upstream of the baghouse) that will allow for either full or slip-stream system testing without affecting the integrity of the Compact CFB boiler to maintain its full load capabilities. Presently, it is envisioned that the following emissions reduction testing will take place:

- Honeycombed microfiltration membrane coated barrier filter system – for simultaneous particulate matter and trace element emissions reduction – specifically mercury and lead;

- Advanced SCR system – testing of poison resistant catalyst for NO_x control with units cofiring coal and various biofuels; and
- Electrostatic Precipitators (ESP) – affect of collection efficiency when cofiring coal and various biofuels.

The system design was completed during June 2002 and the feasibility study will be completed by December 2002. Penn State received the design package while this paper was being prepared and must review it internally before sharing its details. Hence, no design specifics or cost details are contained this paper. They will be shared upon review by Penn State (*i.e.*, during the presentation at the conference). A decision will likely be made near the end of calendar year 2002 whether or not to proceed with the boiler project.

CONCLUDING REMARKS

The Pennsylvania State University is performing a feasibility analysis on installing a state-of-the-art circulating fluidized bed (CFB) boiler and ceramic filter emissions control device at Penn State's University Park campus for cofiring multiple biofuels and other wastes with coal. The feasibility analysis is assessing: the economics of producing steam; the economics of off-sets such as utilizing multiple biomass feedstocks and other wastes; the value of a unique CFB to perform research for industry, such as Foster Wheeler, and the availability of funding from multiple sources including University, state, and federal sources.

Activities that have been completed (as of June 2002) include: assembly of system and infrastructure requirements for the system design, a biomass resource assessment, collection and analysis of representative samples, assessment of materials handling, deposition, and emissions issues, the conceptual design, and determining the capital costs. Items in progress include finalizing a multiyear test program to use the CFB boiler system, determining operating costs, assessing availability of funding for the system and test program, and integrating the results into a feasibility study. December 2002 is targeted for the completion of feasibility study with a decision whether or not to proceed likely being made in that same timeframe.

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