**Establishment of an Environmental Control Technology Laboratory
with a Circulating Fluidized-Bed Combustion System**

Quarterly Technical Progress Report

January 1 – March 31, 2005

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ABSTRACT

This report is to present the progress made on the project “Establishment of an Environmental Control Technology Laboratory (ECTL) with a Circulating Fluidized-Bed Combustion (CFBC) System” during the period January 1, 2005 through March 31, 2005. The following tasks have been completed. First, the renovation of the new Combustion Laboratory is nearly complete, and the construction of the Circulating Fluidized-Bed (CFB) Combustor Building is in the final stages. Second, the fabrication and manufacture of the CFBC Facility is being discussed with a potential contractor. Discussions with potential contractor regarding the availability of materials and current machining capabilities have resulted in the modification of the original designs. The selection of the fabrication contractor for the CFBC Facility is expected during the next quarter. Third, co-firing experiments conducted with coal and chicken waste have been initiated in the laboratory-scale simulated fluidized-bed facility. The experimental results from this study are presented in this report. Finally, the proposed work for the next quarter is described in this report.

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1. EXECUTIVE SUMMARY

The following progress has been attained during this quarter (January 1, 2005 through March 31, 2005). First, the renovation of new Combustion Laboratory is near complete, and the Circulating Fluidized-Bed Combustor (CFBC) Building has been erected. The scheduled move-in date for the Combustion Laboratory is June 1, 2005. Second, the fabrication and manufacture of the CFBC facility was discussed with a potential contractors, Sterling Boiler & Mechanical, Inc. in Evansville, Indiana. According to Sterling's comments and suggestions which are based on the available materials and current machining capabilities, some original designs have been modified. Third, the co-firing of chicken waste and coal with different blend ratios have been initiated in the laboratory-scale simulated fluidized bed facility. The pollutant emissions from the co-firing of chicken waste and coal were monitored. Finally, the work planned in the next quarter is introduced, and the reasons for delays incurred in some of the tasks are discussed.

2. EXPERIMENTAL

2.1. Renovation of Combustion Laboratory and Construction of CFBC Building

The renovation of the Combustion Laboratory nearly complete. Currently, the office furniture and indoor decorations are being installed. The move-in date for Combustion Laboratory is scheduled for June 1, 2005. The CFBC Building has been erected, and all steel frame structures have been completed. Construction efforts are now focused on the outside wall of the CFBC Building. Figure 1 shows the completed steel frames for the CFBC Building.

2.2. Design and Manufacture of CFBC Facility

After several potential manufacturers were contacted, Sterling Boiler & Mechanical, Inc. was considered as a candidate to fabricate CFBC Facility. According to Sterling's comments and suggestions which are based on the available materials and current machining capabilities, some of the original designs have been modified as follows:

- a. Reduce the overall height of the CFBC Facility. Since the distance between the CFBC and the declined ceiling of CFBC Building is too narrow to operate a crane conveniently, one segment (5ft) of CFBC riser will be removed. Therefore, the net height of CFBC Facility decreases from 68ft to 63ft. As a result of this change, the

sight glasses, which are used to observe the combustion inside the CFBC Facility, have been relocated along the riser and downcomer of CFBC Facility.

Figure 1. The completed steel frame of the CFBC Building

- b. Resize the sight glasses. Since the maximum length of the available quartz glass on the market is 12 inches, the sight glasses deployed on the coal feeding pipes and downcomer of CFBC Facility have to be reduced their sizes.
- c. Rearrange the thermocouple, pressure sensor, and sampling ports. The thermocouple, pressure sensor, and gas/solid sampling ports have been designed. Based on the change of the overall height of CFBC Facility, these ports have been relocated along the riser and downcomer of CFBC.
- d. Redesign the coal, limestone, and waste material bunkers. Based on the different the feeding rates of coal, limestone, and waste materials, the coal, limestone, and waste material bunkers have been redesigned with different volumes.
- e. Replace the Class 150lb flanges with the Class 300lb flanges at the maximum load places at the riser of CFBC. To increase the strength against the tensile and compressive stresses at the maximum load locations at the riser of CFBC, the Class 300lb flanges have been employed to replace the Class 150lb flanges at three locations -- the bottommost flange of the middle group and the upmost flanges of the lower and upper groups.

Currently, Sterling Boiler & Mechanical, Inc. is reviewing all modified drawings. The official contract for fabricating CFBC system is expected to be released in May 2005.

2.3 Experiments on a Laboratory-Scale Simulated Fluidized Bed Combustor

2.3.1. Background of co-firing of chicken waste and coal

The utilization of chicken waste from the poultry industry has received much attention in recent years. This is the result of locating an area large enough to accommodate the ever-increasing quantities of waste in landfills and its subsequent environmental implications. One of the alternative disposal routes for chicken waste is direct combustion. Direct combustion offers the potential to provide for both heating of poultry houses and large-scale schemes involving power generation or combined heat and power. However, the high moisture and ash content as well as low heating value of the chicken waste could create problems such as sustaining steady and complete combustion of the chicken waste alone. Therefore, co-firing of chicken waste with coal is considered as a feasible means. On the other hand, co-firing of chicken waste with coal could bring the following benefits: First, sulfur dioxide (SO_2) emissions could be reduced by the

very low sulfur content of chicken waste. This attribute is particularly desirable when co-firing with high-sulfur coal. Second, the nitrogen in chicken waste exists in two forms: inorganic nitrogen and ammonia nitrogen. The ammonia, which serves as an in situ thermal DeNO_x source, could reduce nitrogen oxide (NO) to molecular nitrogen. Hence, co-firing chicken waste with coal could effectively abate nitrogen oxides (NO_x) emission levels. Finally, the mercury content in chicken waste is very low, but the chlorine content is much higher than that in coal. These characteristics could be beneficial to capturing mercury emissions from the coal combustion process since chlorine can transform elemental mercury to oxidized mercury that is easily captured because of its solubility.

Compared with the conventional combustion technology, fluidized-bed combustion is considered as an optimal technology to dispose the animal waste with energy recovery. The ability of fluidized-bed combustion to accept fuels with a relatively high ash and moisture content combined with the low cost associated with fuel preparation, operational flexibility with regard to ash collection and easy control for pollutant emissions make this technology especially suitable for animal wastes. The objective of this work is to investigate the pollutants emissions from co-firing chicken waste with coal and optimize the combustion parameters in a laboratory-scale atmospheric pressure fluidized-bed combustor. Laboratory-scale tests would provide the essential information needed to operate on the bench -scale CFBC Facility.

2.3.2. Experimental Setup

To study the combustion behaviors of co-firing of chicken waste and coal, the experiments were conducted in a laboratory-scale fluidized-bed combustor (FBC). This FBC Facility is made of a 3" I.D. stainless steel pipe and is 3' in height. Figure 2 is a photograph of the laboratory-scale FBC Facility. The electric heater, which consists of a total of four silica carbon rods, is used to heat the FBC to the desired temperature from the outside. Heat loss is minimized by wrapping refractory and insulation materials outside the electric heater. A temperature controller is employed to control the bed at the desired temperature. Compressed air is supplied into this FBC through a bottom windbox and a gas distributor. Coal is fed continuously from the top into the FBC by a screw feeder with carrying air. The flue gas exiting from the top of the FBC is cleaned by a cyclone, cooled, and sent to a flue gas analyzer to measure its composition. The bed height was controlled by adjusting the inserted height of the discharge tube from the bottom. The bed materials including the coal ash and inert sand came out

the combustor through a discharge tube. The fly ash was collected at the bottom of the cyclone. A secondary air nozzle, which is a series small holes arranged on a ring of $\frac{1}{4}$ " stainless steel tubing, was inserted into the furnace and located above the bed surface in order to promote the mixing of air with fuel and to supply the oxygen for the volatiles to burn completely in the freeboard.

Figure 2. Laboratory-scale fluidized-bed combustion system

2.3.3 Bed Materials

Due to its availability, abundance, and inert nature and high melting point, silica sand was selected as the bed material in the fluidized-bed combustor. Silica sand was sized in the range of 0.6 to 0.85mm by sieving. The static bed height was maintained at about 6" inch.

2.3.4 Experimental Procedure

To initiate steady combustion and stable fluidization, it is essential to heat up the inert bed material above the ignition temperature of the fuel. Once the desired temperature is reached, the fuel is slowly fed into the bed from the top of the furnace through a fuel falling tube. To increase the residence time of the fuel inside the bed, the fuel falling tube is inserted into the dense zone of the fluidized bed. For each test about 1.0-1.5 hours is required for the bed to reach the steady state condition at the beginning. The overall duration of each test is about six hours. The criteria of a steady-state condition includes having steady bed temperature and stable pressure drop caused by the air going through the dense zone of the fluidized bed. During the test period, the flue gas compositions such as oxygen (O₂), carbon monoxide (CO), NO_x, and SO₂ are measured using a Tempest 100 flue gas analyzer. At the same time, the bottom ash discharged from the dense zone and the fly ash captured by the cyclone are collected for each test. The mercury content in the bottom and fly ash is analyzed in Western Kentucky University's Coal Analysis Laboratory.

3. RESULTS AND DISCUSSION

3.1. Analysis of Chicken Waste and Coal

Table 1. Characteristics of chicken waste and tested coal

Fuel	Moisture (%)	Ash (%)	Volatile Matter (%)	C (%)	H (%)	O (%)	N (%)	S (%)	Hg (ppm)	Cl (ppm)	Heating Value (Btu/lb)
CW	11.32	27.59	50.79	28.18	4.98	3.39	35.00	0.86	<0.01	11639	5074
Coal	2.62	9.64	36.56	71.31	5.28	1.43	8.82	3.52	0.13	1537	12948
CW/ Coal in 1:1	6.97	18.62	43.68	49.75	5.13	2.41	21.91	2.19	0.07	6588	9011

The ultimate and proximate analysis of both chicken waste and coal are presented in Table 1. It is clear that the chicken waste is characterized by the presence of high oxygen, moisture, and ash. This contributes to the lower heating value of the chicken waste, which is about 60% less than the coal. Another aspect of importance with regard to the nature of chicken waste is that the volatile matter content is high but with very little of fixed carbon content. This means that most of the combustion will take place in the gas phase due to the high volatile matter

in chicken waste. Compared the feed coal, the chlorine and nitrogen contents of chicken waste are much higher, while the sulfur content in chicken waste is relatively lower. Hence, these characteristics could result in that the combustion characteristics of co-firing of chicken waste with coal could be very different to the combustion of coal alone.

3.2 Gaseous Pollutant Emissions

Total two sets of combustion test were performed in this period. (1) Combustion of coal alone with the secondary air. (2) Co-combustion of chicken waste with coal with and without secondary air. The bed temperature was maintained in the range of 830~850°C during testing. The oxygen concentration was maintained in the range of 6.8~7.4%. The blend ratio of chicken waste with coal is 1:1 on a weight basis. In these tests, the gaseous pollutant emissions, such as CO, NO, and SO₂, were monitored.

Figure 3 CO emission concentrations at different operation modes

Figure 3 gives the comparison of CO emission concentration for different operating conditions. The experimental data indicated that CO emissions from the co-combustion of chicken waste with coal decreased from 2143ppm to 1055ppm when the secondary air was

introduced into the freeboard. This phenomenon shows that the secondary air introduced into the freeboard helps the volatile matter released by the chicken waste to be burned completely before it leaves the freeboard of fluidized-bed combustor. This explanation is supported strongly by the low CO emissions from combustion of coal alone. From these experimental results, it can be concluded that the secondary air should be supplied sufficiently in the freeboard of fluidized-bed combustor in order for the volatile matter contained in chicken waste to be burned completely. This is accomplished by augmenting the mixing between the volatile matter and air, and increasing the residence time of the volatile matter in the freeboard of the fluidized-bed combustor.

Figure 4. NO emission concentrations at different operation modes

Figure 4 presents the variation of NO emissions with the operation conditions. As shown in Figure 4, the minimum NO concentration in the flue gas occurred in the combustion of coal alone, while the maximum NO emission took place in the co-firing of chicken waste and coal in 1:1 ratio without the secondary air injection. Based on the ultimate and proximate analysis of chicken waste and coal, the nitrogen content in coal is 8.82%, while nitrogen content in the blend of chicken waste and coal in 1:1 ratio reaches 21.91%. This is the reason that the NO emissions from co-firing of chicken waste and coal were higher than that from the combustion of coal alone.

Although the nitrogen content in the blend of chicken waste and coal was 2.5 times as great as that in coal, NO emissions from co-firing of chicken waste and coal were much lower than that expected when compared with the combustion of coal alone. It suspected that the ammonia released from chicken waste, which were proven in previous studies, could reduce NO to N₂ significantly. When the secondary air was injected into the freeboard, the NO level in flue gas was decreased for co-firing of chicken waste and coal. As shown in Figure 4, the NO concentration was almost identical to that from the combustion of coal alone. Two possible causes could result in this fact. The first reason is that staging combustion could decrease the generation of thermal NO. Second, the mixing caused by the secondary air turbulence could be beneficial to the reduction of NO by the ammonia.

Figure 5. SO₂ emission concentrations at different operation modes

Figure 5 shows the change of SO₂ concentration with the different operation conditions. SO₂ concentration reached about 1600ppm for the combustion of coal alone because of the high sulfur content in coal. For the co-firing of chicken waste and coal, SO₂ emission kept at a low level – below 600ppm, no matter whether the secondary air was injected or not. First, the addition of chicken waste into coal lowered the sulfur content in the mixture of fuels. Second, the ash content increased significantly by blending the chicken waste with coal. Possibility the

addition ash augments the content of calcium carbonate (CaCO_3) or calcium hydroxide (Ca(OH)_2), which can absorb SO_2 in the bottom and fly ash. More evidence is needed to support this point by analyzing the compositions of bottom and fly ash to determine whether the amount of CaCO_3 or Ca(OH)_2 increases in the bottom and fly ash for chicken waste and coal mixtures.

3.3 Mercury Emission in Particulate Phase

Table 2 shows the content of mercury (Hg) in fly ash and bottom ash collected during the combustion tests. It was found that the content of mercury in the bottom ash is negligible. This is because all mercury compounds (both inorganic and organic) exist as elemental mercury in the gas phase under such high temperature conditions. However, the content of mercury in fly ash for co-firing of chicken waste and coal with secondary air penetration was 2.5 times of that for the combustion of coal alone. The main reason is that the Deacon reaction as shown in Equation (1) took place with copper or other metals serving as catalysts due to high chlorine content in the chicken waste.

The chlorine contributes to the conversion of Hg^0 to Hg^{2+} in the flue gas, and Hg^{2+} bonds much easier with the fly ash. From Table 2, it can also be shown that the secondary air enhanced the bondage of mercury with the fly ash. The first reason is that the additional oxygen provided by the secondary air drove the reversible Deacon reaction to generate more chlorine, which is beneficial to convert Hg^0 to Hg^{2+} . The second reason is that the secondary air created a good mixture between solids and flue gas, a fierce turbulence and a dense solid concentration in the free board. These attributes facilitated the combination of fly ash and mercury in the freeboard.

Table 2. Content of mercury in fly ash and bottom ash

----- -----	50% Chicken Waste/ 50% Coal				100% Coal
	Without Secondary Air		With Secondary Air		With Secondary Air
	Bottom Ash	Fly Ash	Bottom Ash	Fly Ash	Fly Ash
Mercury (ppm)	0.003	0.16	0.005	0.35	0.14

4. CONCLUSIONS

During this quarter, the following progress has been attained:

- ◆ The renovation of the new Combustion Laboratory is nearly complete. The move-in date for the Combustion laboratory is scheduled for June 1, 2005. The construction of the CFBC Building progressed on schedule.
- ◆ Sterling Boiler & Mechanical, Inc. was considered as a candidate to be the manufacturer for CFBC Facility. After Sterling reviewed the drawings of CFBC Facility, some original designs were modified the availability of materials and current machining capabilities. The official contract for fabricating CFBC Facility will be awarded to Sterling in May.
- ◆ The co-firing of chicken waste and coal with different blend ratios has been tested on a laboratory-scale simulated fluidized bed facility. The following conclusions can be summarized from the experimental results:
 - CO emissions from co-firing chicken waste with coal were higher than that from the combustion of coal alone, a likely result of the high volatile matter content in chicken waste. However, the secondary air injection can reduce CO emissions significantly.
 - Although chicken waste contains high nitrogen, NO emissions did not show an obvious increase for co-firing of chicken waste and coal with reasonable secondary air injection.
 - The addition of chicken waste was beneficial to the capture of mercury in the fly ash.
 - SO₂ emissions were reduced by addition of chicken waste which has a low sulfur content.

5. FUTURE WORK AND UPDATED SCHEDULE

5.1 Future Work

During the next quarter, the following tasks will be focused on:

- ✦ Release the contract to Sterling Boiler & Mechanical, Inc. to fabricate all parts of the CFBC Facility. Work with Sterling to facilitate the manufacture of the CFBC Facility.
- ✦ Cooperate with architects and constructors to finish the indoor and outdoor portions of the new Combustion Laboratory and CFBC Building. Move in the new Combustion Laboratory. Relocate the laboratory-scale simulated fluidized-bed combustor to the CFBC Building.
- ✦ Continue to conduct experiments on the laboratory-scale simulated fluidized-bed combustor. The following experiments will be carried out on this laboratory-scale Facility in the next quarter:
 - ❖ Measure mercury emissions in the flue gas from co-firing of chicken waste and high sulfur coal.
 - ❖ Set up Polycyclic Aromatic Hydrocarbons (PAHs) sampling system for monitoring PAHs emissions from co-firing of chicken waste and high sulfur coal.

5.2 Updated Schedule

Based on the current status of the project, the updated schedule for calendar Year 2005 is shown in Table 3.

Table 3. Updated Schedule for Calendar Year 2005

Task	Updated Schedule
Release the contract to Sterling Boiler & Mechanical, Inc. for fabricating CFBC Facility	May 10, 2005
Complete tests for mercury emission from co-firing of coal and chicken waste on laboratory-scale fluidized-bed combustor	May 30, 2005
Move into the new Combustion Laboratory	June 1, 2005
Complete construction of the CFB Combustor Building	June 1, 2005
Complete fabrication of component parts of CFBC Facility	July 30, 2005
Initiate installation the bench-scale 0.6MW _{th} CFBC Facility.	August 1, 2005
Complete PHAs emission from co-firing of coal and	August 30, 2005

chicken waste on the laboratory-scale fluidized-bed combustor	
Grand opening of new Combustion Laboratory	October 1, 2005
Complete the installation of bench-scale CFBC Facility	December 15, 2005

ACRONYMS AND ABBREVIATIONS

A	Ash content (wt%)
Btu	British Thermal Unit
C	Carbon content (wt%)
Ca	Calcium
CaCO ₃	Calcium Carbonate
Ca(OH) ₂	Calcium hydroxide
CFB	Circulating Fluidized-Bed
CFBC	Circulating Fluidized-Bed Combustion
Cl	Chlorine content (ppm)
CO	Carbon monoxide
CW	Chicken waste
DOE	U.S. Department of Energy
ECTL	Environmental Control Technology Laboratory
FBC	Fluidized-Bed Combustion
ft	Feet
H	Hydrogen content (wt%)
Hg	Mercury content (ppm)
I.D.	Inside diameter
lb	pound
M	Moisture (wt%)
MW	Million watts
N	Nitrogen content (wt%)
NO	Oxides of nitrogen

NO _x	Nitrous oxide
O	Oxygen content (wt%)
PAH	Polycyclic Aromatic Hydrocarbons
S	Sulfur (wt%)
SO ₂	Sulfur dioxide
V	Volatile matter (wt%)
W	Moisture content (%)
wt	Weight

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